INTERNATIONAL ENERGY AGENCY
energy conservation in buildings and
community systems programme

Air Exchange Rate and Airtightness Measurement Techniques – An Applications Guide

Air Infiltration and Ventilation Centre

AIVC

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Barclays Venture Centre,
Sir William Lyons Road,
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Air Exchange Rate and Airtightness Measurement Techniques – An Applications Guide

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August 1988

This report is part of the work of the IEA Energy Conservation in Buildings & Community Systems Programme.

Annex V Air Infiltration and Ventilation Centre

Document AIC-AG-2-88
ISBN 0 946075 38 7

Participants in this task:

Belgium, Canada, Denmark, Federal Republic of Germany, Finland, Italy, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and United States of America.

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PREFACE

International Energy Agency

In order to strengthen cooperation in the vital area of energy policy, an Agreement on an International Energy Programme was formulated among a number of industrialised countries in November 1974. The International Energy Agency (IEA) was established as an autonomous body within the Organisation for Economic Cooperation and Development (OECD) to administer that agreement. Twenty-one countries are currently members of the IEA, with the Commission of the European Communities participating under a special arrangement.

As one element of the International Energy Programme, the Participants undertake cooperative activities in energy research, development, and demonstration. A number of new and improved energy technologies which have the potential of making significant contributions to our energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRO), assisted by a small Secretariat staff, coordinates the energy research, development, and demonstration programme.

Energy Conservation in Buildings and Community Systems

As one element of the Energy Programme, the IEA encourages research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is encouraging various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programmes, building monitoring, comparison of calculation methods, as well as air quality and inhabitant behaviour studies.

The Executive Committee

Overall control of the R&D programme "Energy Conservation in Buildings and Community Systems" is maintained by an Executive Committee, which not only monitors existing projects but identifies new areas where collaborative effort may be beneficial. The Executive Committee ensures all projects fit into a predetermined strategy without unnecessary overlap or duplication but with effective liaison and communication.

Annex V Air Infiltration and Ventilation Centre

The IEA Executive Committee (Building and Community Systems) has highlighted areas where the level of knowledge is unsatisfactory and there was unanimous agreement that infiltration was the area about which least was known. An infiltration group was formed drawing experts from most progressive countries, their long term aim to encourage joint international research and increase the world pool of knowledge on infiltration and ventilation. Much valuable but sporadic and uncoordinated research was already taking place and after some initial groundwork the experts group recommended to their executive the formation of an Air Infiltration and Ventilation Centre. This recommendation was accepted and proposals for its establishment were invited internationally.

The aims of the Centre are the standardisation of techniques, the validation of models, the catalogue and transfer of information, and the encouragement of research. It is intended to be a review body for current world research, to ensure full dissemination of this research and, based on a knowledge of work already done, to give direction and firm basis for future research in the Participating Countries.

The Participants in this task are Belgium, Canada, Denmark, Federal Republic of Germany, Finland, Italy, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and the United States of America.

ACKNOWLEDGEMENTS

The preparation of this guide depended on the effort and cooperation of many individuals and organisations. In particular the material presented in chapter 6 is based on information received from research workers, who have gained experience developing and using specific measurement techniques. In addition valuable advice and assistance concerning the content of this publication was gratefully received from all members of the AIVC Steering Group and from those who attended the AIVC UK Advisory Group Measurement Techniques Workshop, the AIVC International Measurement Techniques Workshop and other working meetings.

The author would like to thank Janet Blacknell of the AIVC for her assistance in proof reading this publication.

The illustrations in this document were prepared by Ray Cheesman of Art and Bookwork.

SYMBOLS AND UNITS

Units

The following units are used throughout this document.

Quantity	Unit	Symbol
Energy	Joule	J
Length	Metre	m
Mass	Kilogramme	kg
Power	Watt	W
Pressure	Pascal	Pa
Temperature	Kelvin	K
	Celsius	°C
Time	Hour	h
	Second	s

Symbols

The following symbols are used throughout this document.

C = Tracer gas concentration
Cd = Discharge coefficient
Cn = Nozzle constant
Cp = Specific heat capacity, J kg^{-1} K^{-1}
ρ = Density of air, kg m^{-3}
d = Duct (subscript)
ELA = Equivalent leakage area, m^2
e = Exponential
e = External (subscript)
F = Production rate of tracer
H = Ventilation heat loss, W
I = Injection rate of tracer
i = Internal (subscript)
k = Flow coefficient (m^3s^{-1} at 1 Pa)
ln = Natural logarithm to the base e
M = Mass flow of tracer
m = Measurement period (subscript)
N = Air change rate, h^{-1}
n = Flow exponent
P = Pressure, Pa
ΔP = Pressure differential
Q = Air flow rate, m^3s^{-1}
T = Temperature, K
t = Time
Δt = Time interval
V = Volume, m^3
ω = Fanspeed, s^{-1}

HOW TO USE THIS GUIDE

This guide is concerned with the measurement of those parameters which are important in gaining an understanding of air infiltration and ventilation. The guide has been designed so that the material suited to your particular level of interest or current expertise, is readily accessible. The flow chart in Figure 1 illustrates the structure of the guide.

The introduction provides a general overview of infiltration and ventilation in buildings. Ventilation studies are discussed and the aims of the guide outlined.

Chapter 1 defines the parameters which are important, presents the reasons why they should be measured, and gives a guide to the selection of techniques for particular applications. Summaries of the main techniques available are presented, which are cross referenced with the main body of the guide.

Chapter 2 presents the fundamental theory and practice of measuring air exchange rates. Air exchange between a building and the external environment is examined, as is the air exchange between the various internal spaces of a building.

Chapter 3 presents the fundamental theory and practice of measuring the airtightness of the building envelope. The airtightness of whole buildings and building components is considered. Leakage location and leakage path distribution is also examined.

Chapter 4 discusses some of the specialist equipment and instrumentation required to make air infiltration and ventilation measurements.

Chapter 5 examines standards and regulatory documents which relate to air exchange rate and airtightness measurement techniques.

Chapter 6 contains detailed descriptions of selected measurement techniques. To aid comparison and selection, each technique is presented in a standard format.

Chapter 7 contains descriptions of selected instruments and instrument types. Information is presented in a standard format to aid the location of specific details.

Appendix 1 is a glossary of terms used in the guide relating to air exchange and airtightness measurement techniques.

The guide is presented in a loose leaf format to enable fresh developments in measurement technology to be readily accommodated.

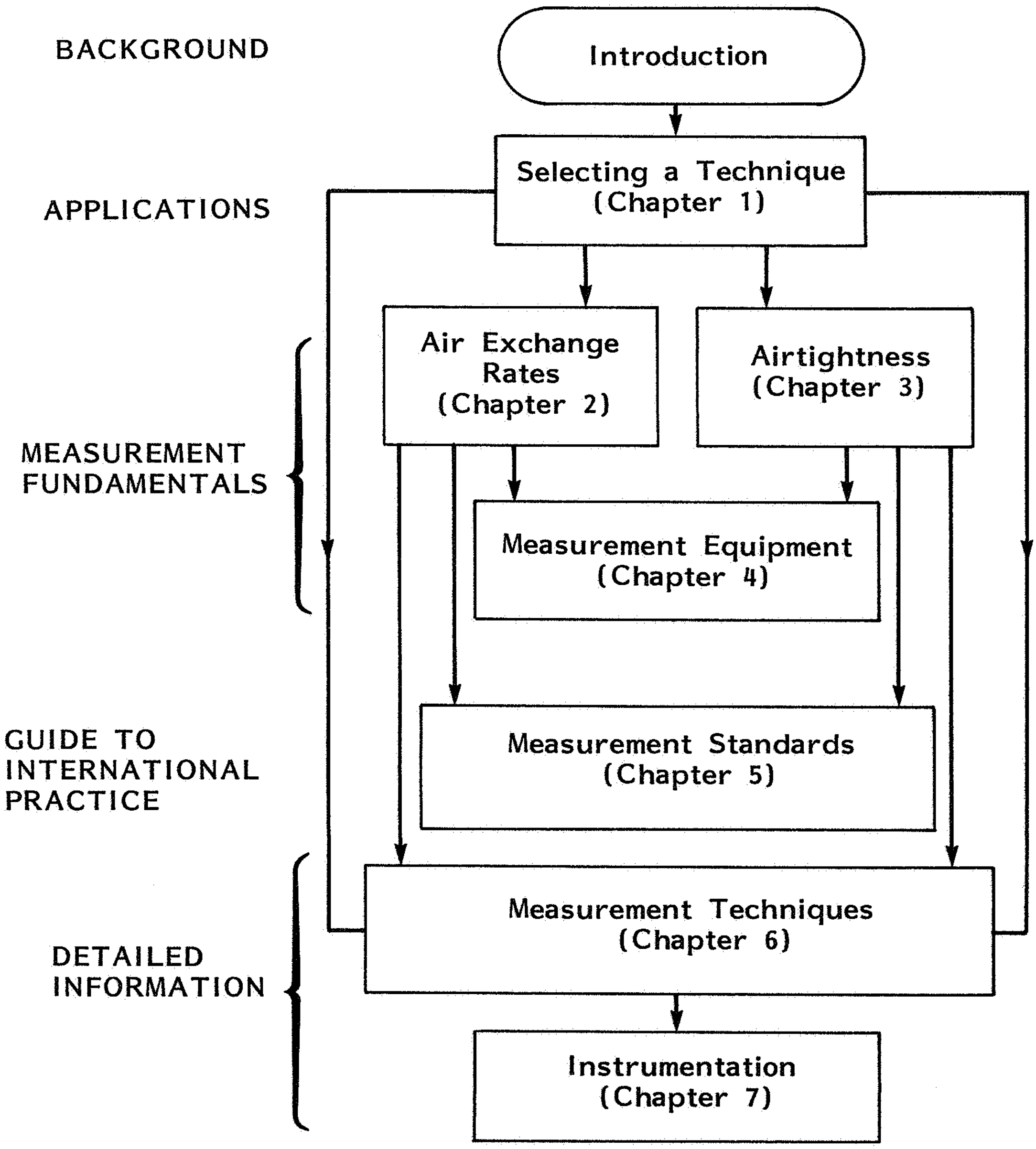

Figure 1 Structure of Guide

INTRODUCTION

The provision of an adequate supply of outdoor air suitable for the needs of the occupants is an important aspect of building design and construction. Ventilation (the transport of air into, through and out of a building) can be promoted by natural or artificial forces. It is necessary to understand this process since it affects both the energy consumption and internal environment of a building. Excessive ventilation will put an undue burden on the building's heating system and may lead to energy wastage, or an unacceptable thermal climate within the building. Insufficient ventilation can cause problems relating to the quality of the air within the building. The internal environment can become uncomfortable or, in extreme cases, harmful to the building occupants. There are a variety of methods by which buildings can be ventilated.

Infiltration

The only means of ventilation in some buildings is air infiltration. This is an entirely passive process and relies upon the fortuitous leakage of air through various cracks and gaps in the building envelope. Typical leakage paths are illustrated in Figure 2.

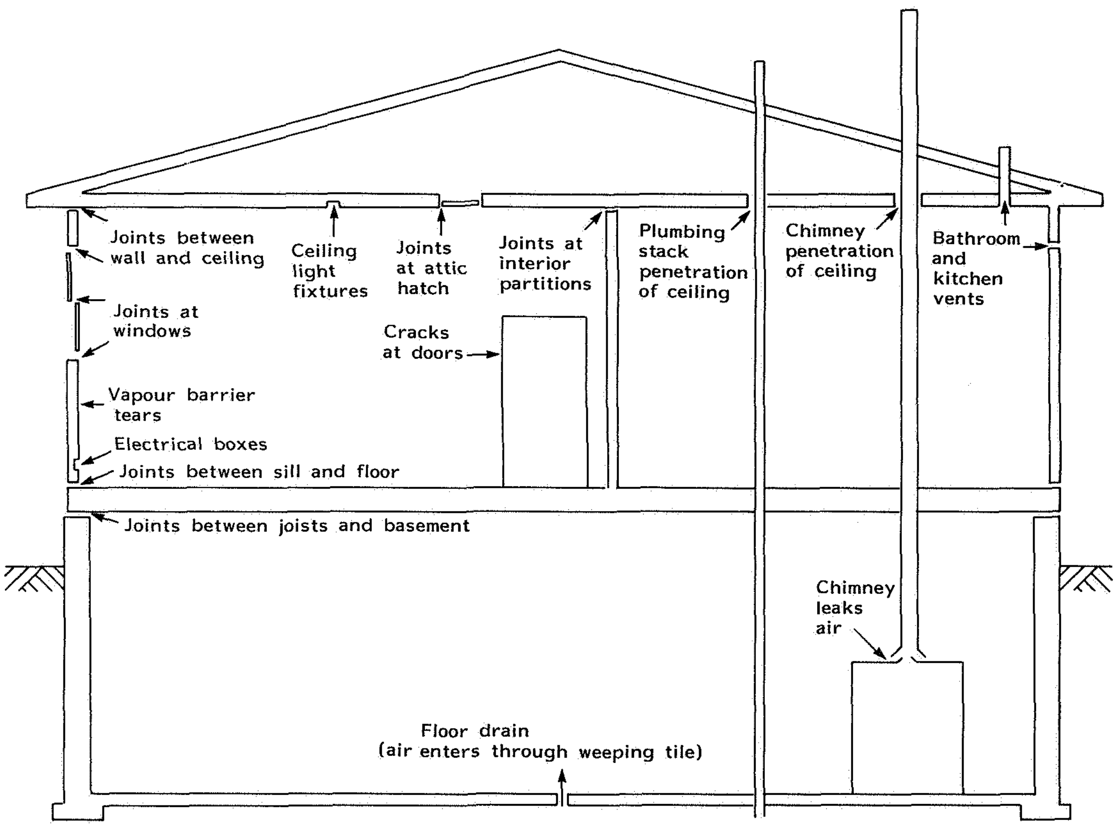

Figure 2 Some typical air leakage paths (after ELMROTH and LEVIN [1983])

The amount of air entering and leaving the building is dependent upon the pressure differential across the building and the characteristics and distribution of the leakage paths in the envelope. Pressure differentials can be caused by the dynamic action of the wind. In this case air will generally enter through cracks on the windward side of the building and leave through similar openings on the leeward side. A difference in air density due to any indoor/outdoor temperature difference will also produce a pressure differential across the building fabric. This is often referred to as the "stack effect". In a heated building air will rise within the structure, entering low down and leaving higher up. Alternatively it may move in the opposite direction if the air in the building is cooler than that outside. In reality the combined effect of wind and temperature produces complex and variable air flow patterns throughout the building.

Natural Ventilation

In the infiltration process the amount of air entering a building is primarily governed by the wind speed, wind direction, indoor/outdoor temperature difference and air leakage characteristics of the building. Because the climate is unpredictable, the specific air flow due to infiltration is a variable parameter which is beyond the control of the occupants. In order to harness the climatic parameters which influence infiltration, buildings can be purposely provided with natural ventilation. This usually consists of controllable apertures which are strategically placed in the building envelope. In this case the positioning of these openings, and the behaviour of the occupants in relation to them, are also factors which influence the rate of air flow into the building.

Mechanical Ventilation

To obtain more control over ventilation it is necessary to introduce mechanical systems into the building. Air can be removed from a building by a mechanical extract fan or it can be driven into a space using a supply system. Extract ventilation (see Figure 3) necessitates the provision of sufficient openings in the building envelope, to ensure that the incoming air may easily replace that which is extracted. Similarly, with a supply system the displaced air has to leave the building through any adventitious or purpose provided openings in the building fabric. Whilst to some extent negating the influence of climatic parameters, the correct functioning of mechanical extract or supply systems will still depend upon the air leakage characteristics of the building envelope. A third type of mechanical system is a combination of the previous two techniques. Known as balanced ventilation, separate systems are used to supply and extract air from the building. In a totally balanced system there is no net pressure effect due to the operation of the fans. Therefore the amount of air entering and leaving the building will be influenced by climatic parameters producing uncontrollable variable pressure differentials across leakage paths in the building fabric.

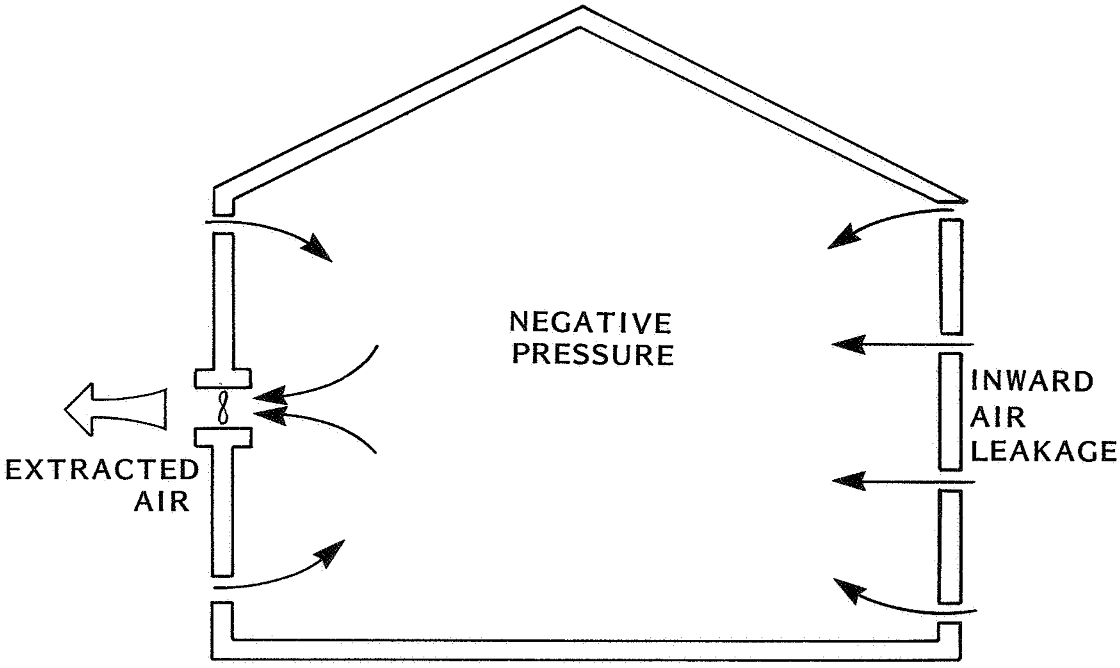

Figure 3 Simple mechanical extract ventilation

Internal Air Movement

The bulk movement of air into and out of a building, whether it is promoted by natural or artificial forces, causes air to flow between the various internal spaces of the building. This exchange of air between internal spaces is of particular importance in relation to the movement of airborne contaminants and moisture from one part of the building to another. An illustration of this would be the effect of air flow between occupied spaces in a dwelling and the cold, unheated roof space above. Here warm moist air could be carried from the living areas and cause condensation problems on the cold internal surfaces of the roof space. Air flow throughout the building cannot be ignored when considering the ventilation process.

Ventilation Studies

It is clear from the preceding discussion that the ventilation of buildings is an important and complex process, which is influenced by a variety of constructional, behavioural and environmental parameters. It is because of these complexities that ventilation is often regarded as one of the least understood aspects of building physics. In recent years research and development in two major areas, mathematical modelling and measurement techniques, has led to a greater depth of knowledge in the field of air infiltration and ventilation. Theoretical methods are now available which enable air exchange rates, both with the environment and between the internal spaces of the building to be evaluated. If these models are to be effectively applied, considerable computational power and large amounts of input data must be used. Alternatively simplified calculation techniques can be utilized. These require less effort to perform but the output is correspondingly limited. Mathematical modelling methods have previously been examined in detail by the Air Infiltration and Ventilation Centre (Liddament [1986]).

Measurement Techniques

A great deal of effort has been devoted to the development of measurement techniques for air infiltration and ventilation. Several of these techniques have been previously examined by the International Energy Agency as part of a wider programme concerning residential building energy analysis, (IEA Annex III [1983]). Now techniques are available which enable the flow rate of air into a building, under normal environmental conditions, to be evaluated. Measurement methods also exist which allow the air exchange rate between the internal spaces of a building to be quantified. Evaluation of the overall airtightness of the building shell has become routine and, in some countries, mandatory. The location and distribution of air leakage sites can be determined, and the air leakage characteristics of specific building components or leakage paths can be evaluated.

Measurement techniques are the fundamental means of acquiring a greater understanding of air infiltration and ventilation, in that they enable primary data to be obtained from the evaluation of existing structures. This document examines, in detail, many of the measurement techniques used for air infiltration and ventilation studies. The broad aims of the guide are to identify the parameters which require evaluating, indicate the variety of measurement techniques which are available, provide detailed information about several techniques, and offer advice regarding the selection of a technique for a particular application.

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CHAPTER 1: Selecting a Technique

CHAPTER 1 SELECTING A TECHNIQUE

1.1 MEASURABLE PARAMETERS

This section examines those parameters which are of interest in air infiltration and ventilation studies.

1.1.1 Air Change Rate

The amount of air which enters and leaves a building is of fundamental importance in air infiltration and ventilation studies. One means of quantifying this movement is to state the the air change rate of a building. This is a measure of the bulk movement of air into and out of a space and is defined as the volumetric rate at which air enters (or leaves) a space divided by the volume of the space. Often the air change rate is expressed in air changes per hour. One air change per hour means that the total volume of air passing through an enclosed space in one hour is equal to the volume of that space (see Figure 1.1.1).

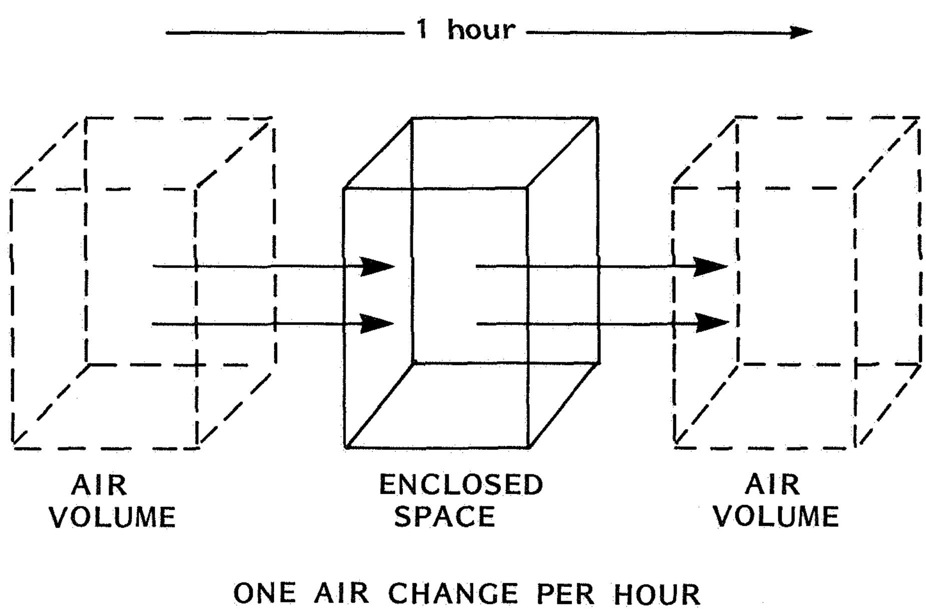

Figure 1.1.1 Schematic illustration of air change rate

The air change rate of a building has major implications with regard to both indoor air quality and energy consumption. The internal environment of a building must satisfy the physiological needs of the occupants. Fundamentally this implies that the occupants should be able to breath in a normal and comfortable manner. Respiration requires the intake of oxygen. Human tolerance to variations in the percentage of oxygen in air is relatively high and it is unlikely that a harmful shortage of oxygen will ever occur in occupied buildings. For a given level of activity, breathing rate is primarily controlled by the concentration of carbon dioxide in the lungs. Outdoor air contains about 0.03% carbon dioxide by volume. If inhaled air contains 2% carbon dioxide the depth of breathing increases. If concentrations reach 3-5% respiration becomes difficult and the atmosphere is noticeably unpleasant. Concentrations above 6% are considered dangerous.

There are two basic approaches to the control of internal pollutants; removal or reduction of the source of the pollutant, and dilution of pollutant once it is airborne. Since exhaled air contains carbon dioxide, outdoor air must be supplied to occupied spaces in order to dilute the internal concentration to an acceptable level. This air flow rate represents a basic ventilation requirement for occupied buildings.

In addition to carbon dioxide there are a number of other internally generated contaminants which pollute indoor air. Internal pollutants are defined as any constituent of indoor air which has a detrimental effect on the health of occupants, reduces amenity, or damages building fabric. Typical indoor contaminants include moisture, gaseous and particulate pollutants from indoor combustion processes (e.g. cooking, heating, tobacco smoking), toxic chemicals and odours from cooking and cleaning, odours from humans, and a wide assortment of chemicals released from building materials and furnishings. Among the less common pollutants are the diverse range of odours, chemicals and particulates which are produced within industrial and commercial buildings. Contaminants are assessed in terms of their source strength, external concentration, discomfort effects and toxicity. In general each pollutant requires a different ventilation rate to ensure adequate dilution and removal. The amount of fresh air supplied to a building must at all times exceed the rate necessary to disperse the pollutant requiring most ventilation. Actual building ventilation requirements are governed by construction methods, functional use, and occupancy levels. A full account of ventilation requirements is given by IEA Annex IX [1987].

In all cases this necessary input of outdoor air gives rise to significant energy losses. Any increase in standards relating to the thermal insulation of buildings tends to increase this significance, as the heat loss due to conduction is diminished. In the case of cold air entering a heated building, and assuming the need to maintain the thermal environment within the structure, the ventilation energy loss H is given by Equation 1.1.1.

$$H = \frac{\rho Cp\ NV}{3600}(T_i - T_e) \qquad (W) \qquad [1.1.1]$$

Where

H = Ventilation heat loss, W

ρ = Density of air, kg m^{-3}

Cp = Specific heat capacity of air, J kg^{-1} K^{-1}

N = Air changes per hour, h^{-1}

V = Volume of space, m^3

T_i = Internal air temperature, K

T_e = External air temperature, K

On substituting typical values for heat capacity and density, Equation 1.1.1 reduces to the approximate expression.

$$H = 0.33\ NV(T_i - T_e) \qquad (W) \qquad [1.1.2]$$

Unless heat recovery is utilised, the heat load due to any ventilation requirement is unavoidable. If, however, the amount of air entering a building exceeds that required to control the internal environment, an unnecessary burden is placed on the heating system. At the design stage the principal task is to minimize energy consumption whilst maintaining indoor air quality. In order to achieve this goal, mathematical methods have been developed and these are now capable of playing an important role in the determination of suitable ventilation strategies. Air change rate is a variable parameter which is dependent upon climatic influences, constructional details, and occupant effects. For existing buildings, practical methods can be utilised to evaluate the air change rate of a building under normal climatic and usage conditions. Measurements of air change rate involve releasing an inert tracer gas in a building and monitoring its concentration with time. Several distinct techniques exist and these are discussed further in Section 2.1. These measurements enable a building to be assessed in terms of its ability to provide adequate ventilation for its occupants, and allows the actual energy loss due to infiltration and ventilation to be evaluated.

1.1.2 Interzonal Air Flow

The bulk movement of air into and out of a building causes air to flow between the various internal spaces of that building. Similarly to air change rate, interzonal air flows are, in terms of both rate and direction, a variable parameter dependent upon construction details, ventilation system operation, climatic effects and occupancy patterns. This variable internal air movement plays a vital role in the distribution of internally generated pollutants throughout the ventilated space.

Often ventilation requirements (see Section 1.1.1) are derived by making the assumption that both the ventilating air and pollutant are uniformly mixed throughout the building. Such conditions may not prevail in practice. Pollution sources are often located at a particular point in a large interior space or confined to an individual room within a building. The pollution from a particular source may not be evenly distributed throughout the ventilated space. In this case it would be incorrect to treat the entire building as a single enclosed space.

A consequence of internal air movement is pollution migration. This can be detrimental to either the fabric or occupants of the building. In hospitals, for example, air flow directions must be kept under control in order to prevent the transport of odours and germs from one area to another. A well known phenomenon is the migration of moisture from production zones such as kitchens to unheated areas such as bedrooms or attics (see Figure 1.1.2). This can cause condensation and mould growth problems. Therefore, in order to gain a complete understanding of the ventilation behaviour of a building it is desirable to know the rate of air exchange between the various internal spaces of the structure.

The techniques used to measure these interzonal air flows are essentially similar to those used to evaluate air change rates in that they involve the use of an inert tracer which is released into the building. However, because of the complex nature of these air flows it may be necessary to utilise more sophisticated equipment and/or more than one tracer gas. The measurement of interzonal air flows using these methods is discussed in further detail in Section 2.2.

1.1.3 Air Leakage Characteristics

Air change rate and interzonal air flows are parameters which are themselves dependent upon a variety of variable influencing factors. A second basic approach in air infiltration and ventilation studies is to try to negate the influence of these variable factors and evaluate the air leakage characteristics of the building fabric only.

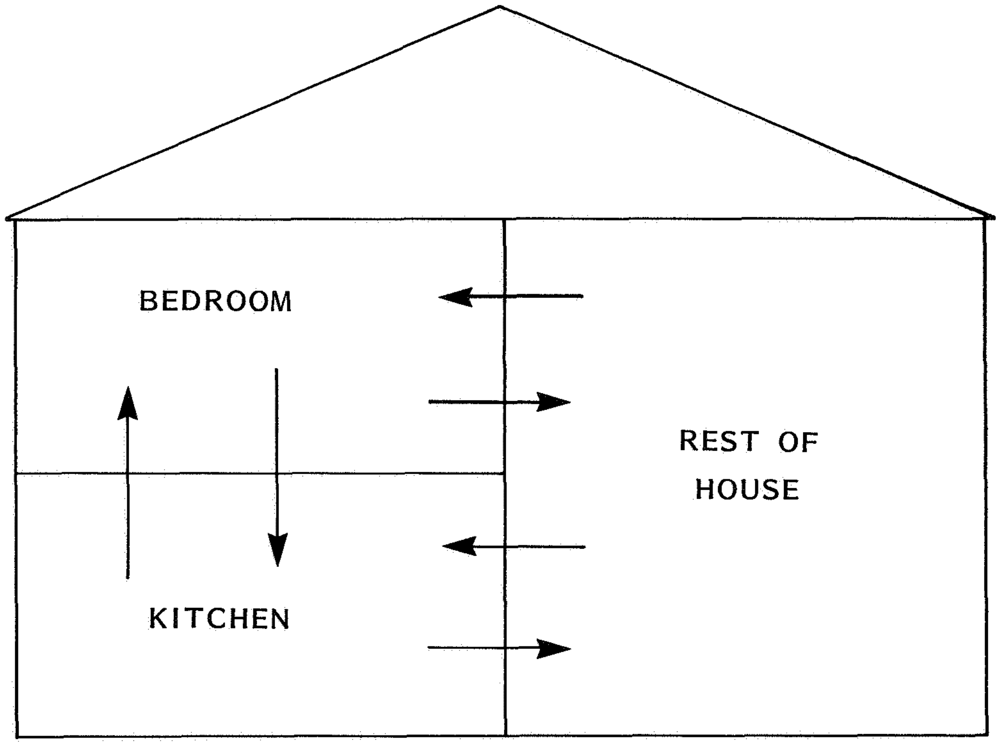

Figure 1.1.2 Interzone air flow. Dwelling divided into three measured zones.

Leakage paths occur in both the external envelope and internal partitions of a building. If there is a pressure difference across a leakage path then air will flow through it. Under normal operating conditions pressure differences are caused by the wind, indoor/outdoor temperature difference, or mechanical ventilation systems. In order to evaluate the leakage performance of the building envelope it is these variable pressures which must be eliminated.

In any building there are many potential leakage sites. These may be either adventitious or intentional. A knowledge of the location of these sites is a first step towards evaluating the envelope in terms of air leakage. Several techniques exist which enable leakage sites to be located. These techniques are discussed in Section 3.4.

In order to characterize the leakage performance of the building completely it is necessary to determine quantitatively the relationship between the air flow through, and the pressure differential across, the leakage paths. Several means of expressing this relationship exist, and these are examined in Chapter 3. The actual relationship may depend upon the nature of the leakage path. Typical crack types are shown in Figure 1.1.3. The building envelope can be examined in its entirety or if more detail is required, relationships for individual building components or leakage paths can be developed.

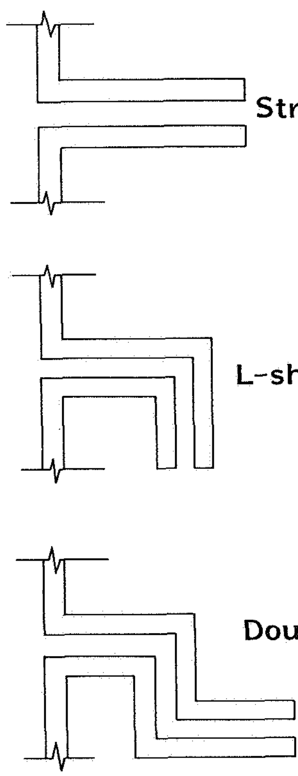

Figure 1.1.3 Common types of cracks encountered in buildings (after ETHERIDGE [1977])

Evaluation of the air leakage characteristics of a structure consists of superimposing a known artificial pressure difference across the envelope or component and measuring the flow rate through it. This type of technique is examined further in Sections 3.1. and 3.2.

1.2 APPLICATION AND SELECTION

This section deals with the selection of measurement techniques for particular applications.

1.2.1 <u>General Process of Selection</u>

The process of selecting a measurement technique takes place in three broadly defined stages.

1 <u>Application</u>

The first task is to clearly define the reason why for any given application, air infiltration and ventilation measurements are required.

2 Parameters

The specific parameters to be measured must then be decided upon. Section 1.1 presents more detailed information regarding the parameters covered by this guide.

3 Selection

Several techniques may be available for the measurement of the required parameters. As well as technical considerations the final choice of technique often may be affected by more mundane issues such as available finance, time allocation, manpower and personnel expertise.

1.2.2 Selecting a Measurement Technique

In order to aid the selection of a measurement technique for any given application two series of tables are presented. Tables 1.2.1 to 1.2.6 describe several applications which require air infiltration and ventilation measurements to be performed. The applications are classified under the following general parameter headings:

Fundamental Data and Research	- Table 1.2.1.
Standards	- Table 1.2.2.
Building Diagnostics	- Table 1.2.3.
Indoor Air Pollution	- Table 1.2.4.
Ventilation Efficiency	- Table 1.2.5.
Input for and Validation of Mathematical Models	- Table 1.2.6.

A brief description of each application is given and the parameters requiring measurement are presented. Finally guidance as to the type of technique(s) suitable for each application is provided.

Tables 1.2.7 to 1.2.11 present summaries of the main measurement techniques examined by this guide. The techniques are grouped under the following general headings:

Air Change Rate Methods	- Table 1.2.7.
Interzonal Air Flow Methods	- Table 1.2.8.
Building Envelope Airtightness Methods	- Table 1.2.9.

TABLE 1.2.1. APPLICATION OF MEASUREMENT TECHNIQUES

FUNDAMENTAL DATA AND RESEARCH

APPLICATION	DESCRIPTION	EVALUATED PARAMETERS	TECHNIQUE
INFILTRATION CHARACTERISTICS	Assessment of climatic influences on air exchange rates for individual buildings	AIR CHANGE RATE (See Table 1.2.7.)	Single tracer gas methods using on site analysis (See Section 2.1.)
		INTERZONAL AIRFLOWS (See Table 1.2.8.)	Multiple tracer gas methods (See Section 2.2.)
		LOCAL CLIMATIC DATA – Windspeed – Wind direction – Indoor/outdoor temperature difference	ON SITE – Anemometer – Wind vane – Thermometers (See Section 4.4.)
INTERCOMPARISON OF BUILDINGS	Simultaneous assessment of several buildings with regard to ventilation behaviour under similar climatic and usage conditions	AIR CHANGE RATE Single measurement	Single tracer gas decay method using grab sampling (See Section 2.1.2.)
		AIR CHANGE RATE Long term average	Single tracer gas constant emission method using grab or passive sampling (See Section 2.1.2.)
		CLIMATIC DATA	If buildings are all in the same area climatic data from a nearby weather station may be used
	Sequential testing of buildings of a similar type to obtain distribution cf leakage characteristics Further checks on individual buildings to assess whether they are comparitively 'tight' or 'loose'	AIR LEAKAGE CHARACTERISTICS OF THE BUILDING ENVELOPE (See Table 1.2.9.)	D.C. pressurization External fan Ideal for dwellings (See Section 3.1.1.) Commercial equipment available (See Section 4.3.)
			D.C. pressurization Internal fan Usually for commerical buildings (See Section 3.1.1.)
			A.C. pressurization Ideal for dwellings (See Section 3.1.2.) Commercial equipment available (See Section 6.9.)
OCCUPANT INFLUENCE	Assessment of effect of intermittent use of openings such as windows and doors	AIR CHANGE RATE In several parts of a building	Single tracer gas methods using automated monitoring such as constant concentration technique (See Section 2.1.3.)
		OCCUPANT BEHAVIOUR	Visual inspection or automated monitoring of openings Questionnaire

TABLE 1.2.2. APPLICATION OF MEASUREMENT TECHNIQUES

STANDARDS

APPLICATION	DESCRIPTION	EVALUATED PARAMETERS	TECHNIQUE
VENTILATION RATE STANDARDS	Evaluation of a building to determine whether ventilation rate requirements are met	AIR CHANGE RATE (See Table 1.2.7.)	Single tracer gas methods (See Section 2.1.)
ENVELOPE AIRTIGHTNESS STANDARDS	Evaluation of newly constructed buildings with regard to airtightness regulations	AIR LEAKAGE CHARACTERISTICS OF BUILDING ENVELOPE (See Table 1.2.9.)	D.C. pressurization Internal or external fan (See Section 3.1.1.)
			A.C. pressurization (See Section 3.1.2.)
COMPONENT AIRTIGHTNESS STANDARDS	Evaluation of leakage characteristics of building components with regard to airtightness regulations	AIR LEAKAGE CHARACTERISTICS OF BUILDING COMPONENTS (See Table 1.2.10.)	D.C. pressurization Site measurement (See Section 3.2.)
			D.C. pressurization Laboratory measurement (See Section 3.2.)

TABLE 1.2.3. APPLICATION OF MEASUREMENT TECHNIQUES

BUILDING DIAGNOSTICS

APPLICATION	DESCRIPTION	EVALUATED PARAMETERS	TECHNIQUE
ENERGY AUDIT	Evaluation of infiltration and ventilation part of heat load on a building	AIR CHANGE RATE Mean value over a period of time, eg heating season (See Table 1.2.7.)	Single tracer gas methods Often long term averaging techniques (See Section 2.1.)
		AIR CHANGE RATE Evaluated from AIR LEAKAGE CHARACTERISTIC DATA (See Table 1.2.6.)	Pressurization methods (See Section 3.1.)
RETROFIT	The qualitative and quantitative assessment of air penetration as a prerequisite for planning an efficient retrofit of a building envelope	AIR LEAKAGE CHARACTERISTICS (See Table 1.2.9.)	Pressurization methods (See Section 3.1.)
		LEAKAGE LOCATION (See Table 1.2.10)	Qualitative methods EXAMPLES: – Thermography – Acoustic location – Smoke visualisation (See Section 3.4.) – Often combined with pressurization methods
	Testing retrofit		
SICK BUILDINGS	Examination of the relationship between building-related illness and inadequate or inappropriate ventilation strategies	AIR CHANGE RATE (See Table 1.2.7.)	Single tracer gas methods Appropriate technique will depend upon actual problem (See Section 2.1.)
		INTERZONAL AIRFLOWS (See Table 1.2.8.)	Multiple tracer gas methods (See Section 2.2.)
		INDOOR AIR POLLUTION	SEE TABLE 1.2.5.
		VENTILATION EFFICIENCY	SEE TABLE 1.2.4.
TROUBLE SHOOTING	This relates to a variety of situations		
	EXAMPLE: Checking whether an excessive air change rate is responsible for a designed heating plant failing to bring a building up to the required internal temperature	AIR CHANGE RATE (See Table 1.2.7.)	Single tracer gas methods a simple inexpensive technique may be preferred

TABLE 1.2.4. APPLICATION OF MEASUREMENT TECHNIQUES

VENTILATION EFFICIENCY

APPLICATION	DESCRIPTION	EVALUATED PARAMETERS	TECHNIQUE
MECHANICAL VENTILATION EFFICIENCY	Evaluation of a mechanical ventilation system's ability to remove pollution eminating from a source within the building	INDICES OF VENTILATION EFFICIENCY A detailed account of these indices can be found in Liddament [1987]	
General methods smaller buildings	Initial uniform concentration of 'pollutant' within the building. Subsequent monitoring of variation of concentration with time	(See Liddament [1987])	Single tracer gas decay rate method (See Section 2.1.1.)
	Ventilation supply air continuously tagged and monitored within the building	(See Liddament [1987])	Single tracer gas Constant emission method Gas injected into duct (See Section 2.1.2.)
	Ventilation supply air intermittently tagged with a pulse of tracer and growth and decay of tracer monitored within the building	(See Liddament [1987])	Single tracer gas Pulse technique
Larger single zone buildings	Evaluation of ventilation efficiency at different points within a large building Tracer gas released at a point within enclosure and integrated concentration with time monitored at exhaust terminal	Transfer index Mean residence time of air (See Liddament [1987])	Single tracer gas pulse technique
Multi-zone buildings	Evaluation of the effectiveness of air distribution systems in multi-zone buildings	AIR CHANGE RATE Outdoor air flow rate into each zone	Single tracer gas methods Usually constant concentration technique (See Section 2.1.3.)
		MEAN AGE OF AIR In each zone	Single tracer gas decay rate Concentration measured in each zone
	Cross transfer of air from one zone to another	INTERZONAL AIRFLOWS (See Table 1.2.8.)	Single tracer gas method Gas released in one zone concentration monitored in others
			Multiple tracer gas methods (See Section 2.2.)
NATURAL VENTILATION EFFICIENCY	Evaluation of efficiency of natural ventilation systems as applied to multi zone dwellings Natural ventilation is dependent upon climatic effects	LOCAL VENTILATION RATE In each zone	Single tracer gas Decay rate technique
		AIR CHANGE RATE Amount of outdoor air entering each room	Single tracer gas Constant concentration method (See Section 2.1.3.)
		INTERZONAL AIRFLOW (See Table 1.2.8.)	Multiple tracer gas methods (See Section 2.2.)
		CLIMATIC DATA – Windspeed – Wind direction – Internal/external temperature difference	SITE DATA – Anemometer – Wind vane – Thermometer

TABLE 1.2.5. APPLICATION OF MEASUREMENT TECHNIQUES

INDOOR AIR POLLUTION

APPLICATION	DESCRIPTION	EVALUATED PARAMETERS	TECHNIQUE
EFFECT OF VENTILATION ON INDOOR AIR POLLUTION	Correlation between indoor air pollution and air change rate	AIR CHANGE RATE (See Table 1.2.7.)	Single tracer gas methods (See Section 2.1.)
		INTERNAL POLLUTANT LEVELS	Several techniques NB: Not examined in this guide
POLLUTION MIGRATION	Evaluation of pollution migration from source areas to regions where the pollution could cause problems	INTERZONAL AIRFLOWS (See Table 1.2.8.)	Multiple tracer gas methods (See Section 2.2.)
		Weighted mean pollutant concentration	Tracer gas method Continuous emission technique Passive sampling (See Section 2.1.2.)

TABLE 1.2.6. APPLICATION OF MEASUREMENT TECHNIQUES

MATHEMATICAL MODELS – INPUT AND VALIDATION

APPLICATION	DESCRIPTION	EVALUATED PARAMETERS	TECHNIQUE
PRESSURE DATA REDUCTION INPUT	Rule of thumb for estimating average air change rate under climatic conditions from airtightness measurements	AIR CHANGE RATE At an imposed pressure difference of 50 Pa	Pressurization methods (See Section 3.1.1.)
VALIDATION	Compare measured and predicted average air change rates	AIR CHANGE RATE (See Table 1.2.7.)	Single tracer gas methods (See Section 2.1.)
REGRESSION ANALYSIS INPUT	Correlation between air change rate and climatic parameters for a particular building	AIR CHANGE RATE Over extended periods (See Table 1.2.7.)	Single tracer gas methods Often constant concentration (See Section 2.1.3.)
		CLIMATIC DATA – Windspeed – Wind direction – Internal/external temperature difference	SITE DATA – Anemometer – Wind vane – Thermometers
SINGLE ZONE NETWORK MODEL INPUT	Model predicts air change rate in a single enclosed space under a variety of design conditions	LEAKAGE DISTRIBUTION Of building envelope (See Table 1.2.11.)	Quantitative methods for leakage location EXAMPLE: Thermography Smoke visualisation (See Section 3.4.)
			Pressurization methods Using reductive sealing (See Section 3.1.1.)
		AIR LEAKAGE CHARACTERISTICS Of external flow paths (See Table 1.2.10)	External component pressurization method Site analysis (See Section 3.2.)
			External component pressurization method Laboratory analysis (See Section 3.2.)
VALIDATION	Compare measured and predicted air change rates	AIR CHANGE RATE (See Table 1.2.7.)	Single tracer gas methods (See Section 2.1.)
		CLIMATIC DATA	Meteorological instruments
MULTI ZONE NETWORK MODEL INPUT	Model predicts air change rate and interzonal airflows in multi-zone buildings	SAME PARAMETERS AS SINGLE ZONE NETWORK MODEL	SEE ABOVE
		LEAKAGE DISTRIBUTION Of internal flow paths (See Table 1.2.10.)	Quantitative location methods (See Section 3.4.)
			Pressurization methods Using reductive sealing (See Section 3.1.1.)
			Pressurization methods Using the balanced fan technique (See Section 3.2.)
		AIR LEAKAGE CHARACTERISTICS Of internal flow paths (See Table 1.2.10.)	Component pressurization methods – Site analysis or – Laboratory analysis (See Section 3.2.)
VALIDATION	Compare measured and predicted air change rates and interzonal air flows	AIR CHANGE RATE In each zone (See Table 1.2.7.)	Single tracer gas methods Usually constant concentration technique (See Section 2.1.3.)
		INTERZONAL AIRFLOWS (See Table 1.2.8.)	Multiple tracer gas methods (See Section 2.2.)

TABLE 1.2.7. SUMMARY OF MAIN MEASUREMENT TECHNIQUES

AIR CHANGE RATE METHODS

TECHNIQUE	EQUIPMENT	MEASURED QUANTITIES	FACTORS AFFECTING SELECTION
SINGLE TRACER GAS DECAY RATE SITE ANALYSIS (Further details in Section 2.1.1.)	*ESSENTIAL* Tracer gas Gas analyser Gas injection device Air sampling tubes and pump Mixing fans Chart recorder *OPTIONAL* Microcomputer	Concentration of tracer gas in measurement space Time (continuous) Building volume	Low cost method Basic equipment readily available Conditions are considered to be constant over decay period Only relative values of tracer concentration are required
SINGLE TRACER GAS DECAY RATE GRAB SAMPLING (Further details in Section 2.1.1.)	*SITE* Tracer gas Gas injection device Air sampling bags or bottles Watch *LABORATORY* Gas analyser *OPTIONAL* Microcomputer	Concentration of tracer gas in collected air samples Time at which samples are obtained Building volume	Low cost method Analysis equipment readily available Delicate analysis equipment need not be moved from safe confines of laboratory Conditions are considered to be constant over decay period Site work can be performed by people with little training If several buildings are being examined simultaneously good coordination is required Risk of sample loss in transit
SINGLE TRACER GAS (Specific – carbon dioxide) DECAY RATE (Further details in Section 6.3.)	Carbon dioxide supply Hand held detector tubes Watch	Amount of carbon dioxide in sample tubes Time at which samples were taken Building volume	Very inexpensive technique May not be as accurate as more sophisticated techniques Analysis becomes more difficult if occupants are present (due to their generation of carbon dioxide)
SINGLE TRACER GAS CONSTANT EMISSION RATE SITE ANALYSIS (Further details in Section 2.1.2.)	*ESSENTIAL* Tracer gas Gas analyser Gas injection device Gas flow meter Air sampling tubes and pump Chart recorder *OPTIONAL* Microcomputer (Almost always used in practice)	Emission rate of tracer into measured space Concentration of tracer gas in measurement space Time (continuous) Building volume	Variation of air change rate with time can be evaluated A period of time may be required for the tracer concentration to reach equilibrium A careful choice of tracer gas and concentration levels must be made in order to avoid consuming large amounts of gas
SINGLE TRACER GAS CONSTANT EMISSION RATE GRAB SAMPLING (Further details in Section 2.1.2.)	*SITE* Tracer injection bag with pump Tracer sample bag with pump Watch/calender *LABORATORY* Gas analyser	Emission rate of tracer into measured space Concentration of tracer in sample bag Period of measurement Building volume	Low cost method Delicate analysis equipment need not be moved from safe confines of laboratory Provides no detailed information about variation of air change rate with time Ideal in situation where air change rate is unlikely to vary much
SINGLE TRACER GAS CONSTANT EMISSION RATE PASSIVE SAMPLING (Further details in Section 2.1.2.)	*SITE* Liquid tracer source Tracer gas sampling device Watch/Calender *LABORATORY* Thermal desorber (releases tracer from sampling device) Gas analyser	Emission rate of tracer into measured space Concentration of tracer gas in sampling device Period of measurement Building volume	Site equipment costs are low Site equipment can be delivered and returned by mail Ideal in situations where air change rate is unlikely to vary much Multiple samples can be taken using more complex site equipment Laboratory equipment costs are high
SINGLE TRACER GAS (Specific carbon dioxide) CONSTANT EMISSION OCCUPANT GENERATION (Further details in Section 2.1.2.)	Occupants - for carbon dioxide generation Gas analyser Air sampling tubes and pump Watch Means of recording number of occupants e.g. chart	Concentration of carbon dioxide in occupied space Concentration of carbon dioxide in outdoor air Number of occupants (continuous) Time (continuous) Building volume	Relatively inexpensive technique Ideal for cases where all air inflow is from outside Analysis more complex if above does not hold Accurate observation of occupancy levels must be made – this could be difficult in large buildings
SINGLE TRACER GAS CONSTANT CONCENTRATION (Further details in Section 2.1.3.)	Tracer gas Mixing fans Gas analyser Gas injection and control device Gas flow meter Valve switching device Microcomputer Control software	Emission rate of tracer into measured space Concentration of tracer gas in measured space Time (continuous) Building volume	High cost method Sophisticated technique providing very detailed information Can operate for prolonged periods without supervision Equipment packages semi-commercially available

TABLE 1.2.8. SUMMARY OF MAIN MEASUREMENT TECHNIQUES

INTERZONAL AIR FLOW METHODS

TECHNIQUE	EQUIPMENT	MEASURED QUANTITIES	FACTORS AFFECTING SELECTION
MULTIPLE TRACER GAS DECAY RATE (Further details in Section 2.2.)	*ESSENTIAL* Tracer gases Gas analyser Gas injection device Air sampling tubes and pump Zone selection device Mixing fans Chart recorder *OPTIONAL* Microcomputer	Concentration of each tracer gas in each zone Time (continuous) Zone volumes	Provides detailed information about instantaneous internal air flow patterns A knowledge of complex mathematics and a high degree of operator skills are required Equipment relatively inexpensive Usual use is in research work Practical with up to four gases Computer required for analysis
MULTIPLE TRACER GAS CONSTANT EMISSION RATE PASSIVE SAMPLING (Further details in Section 2.2.)	*SITE* Liquid tracer sources Tracer gas sampling devices Watch/calender *LABORATORY* Thermal desorber (releases tracer gas from sampling device) Gas analyser	Emission rate of each tracer into measured zone Concentration of each tracer gas in each sample device Period of measurement Zone volumes	Site equipment costs are low Site equipment can be delivered and returned by mail No detailed information about variation of air flow Useful for pollution migration studies Laboratory equipment costs are high Practical with up to four gases Computer required for analysis
MULTIPLE TRACER GAS CONSTANT CONCENTRATION (Further details in Section 2.2.)	Tracer gases Gas analyser Gas injection and control devices Gas flow meters Zone selecting device Microcomputer Control software	Emission rate of each tracer into measured zone Concentration of each tracer in each zone Time (continuous) Zone volumes	Provides detailed continuous information about internal airflow patterns Highly sophisticated and expensive technique Practical with up to eight gases

TABLE 1.2.9. SUMMARY OF MAIN MEASUREMENT TECHNIQUES

BUILDING ENVELOPE AIRTIGHTNESS METHODS

TECHNIQUE	EQUIPMENT	MEASURED QUANTITIES	FACTORS AFFECTING SELECTION
DC PRESSURIZATION EXTERNAL FAN (Further details in Section 3.1.1.)	*ESSENTIAL* Door or window panel for locating fan in envelope Fan Fan flow controller Flow rate measurement device Differential pressure measurement device *OPTIONAL* Anemometer	Rate of airflow into building Pressure differential across building envelope Building volume and/or Envelope area	Low equipment cost especially for small buildings Commercially available equipment Short measurement period (about one hour) Higher cost for larger buildings due to increased equipment and transportation expense Displaces large volumes of air from building Subject to wind effect errors
DC PRESSURIZATION INTERNAL FAN (Further details in Section 3.1.1.)	Suitable air handling system within building Means of measuring total flow rate through system Differential pressure measurement device	Rate of airflow through air handling system Pressure differential across building envelope Building volume and/or Envelope area	Dispenses with need for transportation of large fans Ideal for larger buildings Requires knowledge of air handling system operation Achievable pressure differential range may be limited Subject to wind effect errors
AC PRESSURIZATION (Further details in Section 3.1.2.)	Door panel Volume drive bellows Volume displacement monitor Pressure measurement device Control hardware Control software	Bellows volume change Pressure variation within building Building volume and/or Envelope area	Operates at pressures which drive infiltration Displaces small volume of air from the building Ideal for small buildings Does not permit the testing of 'large' leaks e.g. open windows Continuous evaluation of leakage Less subject to wind effect errors than D.C. pressurization

TABLE 1.2.10. SUMMARY OF MAIN MEASUREMENT TECHNIQUES

BUILDING COMPONENT AIRTIGHTNESS METHODS

TECHNIQUE	EQUIPMENT	MEASURED QUANTITIES	FACTORS AFFECTING SELECTION
DC PRESSURIZATION COLLECTOR CHAMBER (Further details in Section 3.2.)	*ESSENTIAL* Collector chamber (Sealing box) Fan Flow rate measurement device Differential pressure measurement device *OPTIONAL* Second fan to balance pressure between collection chamber and room	Airflow rate through component Pressure difference across component Component dimensions	Relatively low cost method Ideal for examination of buildings which have a large number of replicated components Time and skill is required to adjust the collector chamber to a given component
DC PRESSURIZATION LABORATORY TESTING (Further details in Section 3.2.)	Test chamber Fan Flow rate measurement device Pressure differential measurement device	Airflow rate through component Pressure differential across component Component dimensions	High initial cost to build facility Good design allows many types of components to be tested Results may be 'better' than site measurements due to controlled workmanship
DC PRESSURIZATION REDUCTIVE SEALING (Further details in Section 3.1.1.)	Pressurization equipment (See Table 1.2.9.) Sealing products For example: plastic sheet Sticky tape	Air flow rate through envelope Pressure difference across envelope Building volume Degree of sealing (Type, number and location of sealed components)	Low cost method Patience and skill are required to seal components effectively Does not apply to components which cannot be isolated Similar work can be performed with AC pressurization
DC PRESSURIZATION Balanced fan (Further details in Section 3.2.)	Two or more sets of pressurization equipment (See Table 1.2.9.) Pressure differential measurement and control devices	Air flow rate through main test fan Pressure difference across test component Pressure difference across other partitions (Should be maintained at zero) Building volume	Increase cost due to more equipment Skill required to balance pressure differentials In complex buildings several sets of equipment (more than three) may be required or several sets of measurements must be made More susceptible to wind effect errors than single fan method
FLOW RATE METER (Further details in Section 3.2.)	*ESSENTIAL* Pressure compensating flow rate meter Flow collection chamber *OPTIONAL* DC pressurization equipment (See Table 1.2.9.)	Airflow rate through measured component Component dimensions	Can measure natural air flow rate through facade components Flow collection chamber does not have to provide an air tight seal Limited flow rate range Large leaks in facade cannot be evaluated Large internal leaks make pressure compensation difficult

TABLE 1.2.11. SUMMARY OF MAIN MEASUREMENT TECHNIQUES

LEAKAGE LOCATION AND QUALITATIVE METHODS

TECHNIQUE	EQUIPMENT	MEASURED QUANTITIES	FACTORS AFFECTING SELECTION
THERMOGRAPHIC VISUALISATION (Further details in Section 3.4.)	*ESSENTIAL* Thermal imaging camera *OPTIONAL* DC pressurization equipment (See Table 1.2.9.)	Facade surface temperature distribution	High equipment cost Information obtained rapidly Skill required to interpret thermographs Fan pressurization may enable air leaks to be more readily detected
SMOKE VISUALISATION (Further details in Section 3.4.)	*ESSENTIAL* Smoke production device *OPTIONAL* DC pressurization equipment (See Table 1.2.9.)	Examination of smoke movement	Low equipment cost Simple to use although experience is required to use method effectively Time consuming unless a limited investigation is performed
ACOUSTIC LOCATION (Further details in Section 3.4.)	Sound source Sound detection device	Volume of sound at locations around building envelope	Low equipment cost Experience is required to use method effectively Prone to spurious noise
HELIUM BUBBLE VISUALISATION	Helium supply Bubble generator Soap solution	Examination of bubble movement	Low equipment cost Ideal for laboratory use Experience required to use method effectively Bubble generator prone to blockage

Building Component Airtightness Methods	- Table 1.2.10.
Leakage Location and Qualitative Methods	- Table 1.2.11.

For each technique a list of equipment is given and the actual measured quantities are presented. Specific factors which may govern the selection of a particular technique are indicated, and each technique is cross-referenced with the main body of the guide.

The information presented in this Section and Tables 1.2.1 to 1.2.11 does not necessarily preclude the use of other techniques for these or any other infiltration and ventilation related applications.

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CHAPTER 2: Measurement of Air Exchange Rates

CHAPTER 2 MEASUREMENT OF AIR EXCHANGE RATES

This chapter examines the fundamental theory and practice of measuring air change rates and interzonal air flows.

2.1 MEASUREMENT OF AIR CHANGE RATE

The direct measurement of the bulk movement of air into and out of a space involves the release and monitoring of a non-toxic gas within the enclosure. The rate of change in concentration of the gas is given by the amount of gas leaving the space subtracted from the amount of gas entering the space. This is equal to the difference between the outdoor and indoor concentrations of the tracer multiplied by the rate at which air is exchanged with the atmosphere, plus a generation term which is a measure of the rate at which the tracer is produced or injected. The generalised tracer mass balance equation can be presented as

$$V\frac{dC}{dt} = Q[C_e - C_{(t)}] + F \qquad [2.1.1]$$

Where

V = Effective volume of enclosure, m^3

Q = Specific air flow rate through enclosure, m^3s^{-1}

C_e = External concentration of tracer gas

$C_{(t)}$ = Internal concentration of tracer gas at time t

F = Production rate of tracer by all sources within the enclosure

This continuity equation forms the essence of tracer gas measurements. There are three basic approaches to solving Equation 2.1.1. These are discussed below:

2.1.1 Concentration Decay Method

Theoretical considerations

With this method a one-time injection of tracer gas is made. The gas is allowed to mix with the internal air, this may be promoted by small electric fans or the building air handling system. The concentration of gas, over a given time interval, is then monitored with a suitable detector. This method requires a quite complex solution to the continuity equation. Following cessation of gas injection, assuming that the concentration of tracer gas in outdoor air is negligible, and that there are no incidental sources of tracer within the building, the continuity equation, Equation 2.1.1 reduces to

$$V\frac{dC}{dt} = -Q\,C_{(t)} \qquad [2.1.2]$$

This can be rearranged to give:

$$\frac{dC}{C_{(t)}} = -\frac{Q}{V}\,dt \qquad [2.1.3]$$

Assuming a constant flow rate, Q ,and solving by integration

$$\int_{C_{(0)}}^{C_{(t)}} \frac{dC}{C_{(t)}} = -\frac{Q}{V}\int_{t=0}^{t=t} dt \qquad [2.1.4]$$

Where

$C_{(0)}$ = Concentration of tracer gas at time t = 0

Hence:

$$\ln C_{(t)} - \ln C_{(0)} = -\frac{Q}{V}t \qquad [2.1.5]$$

On solving Equation 2.1.5 the variation of tracer gas concentration with time is given by

$$C_{(t)} = C_{(0)}\,e^{-\frac{Q}{V}t} \qquad [2.1.6]$$

Where

$\frac{Q}{V}$ = N = Air change rate per unit time

Therefore if N remains constant over the measurement period, the tracer gas concentration will exhibit a negative exponential decay. For practical purposes, the tracer gas concentration is often plotted against elapsed time in hours on semi-log paper. The negative slope of the line is then equal to N (see Figure 2.1.1) and the air change rate is normalized to indoor temperature and expressed in air changes per hour. If the actual volumetric air flow rate into the building is required, then the determined value of N must be multiplied by the building volume. The evaluation of this volume is often difficult (see Section 2.1.4).

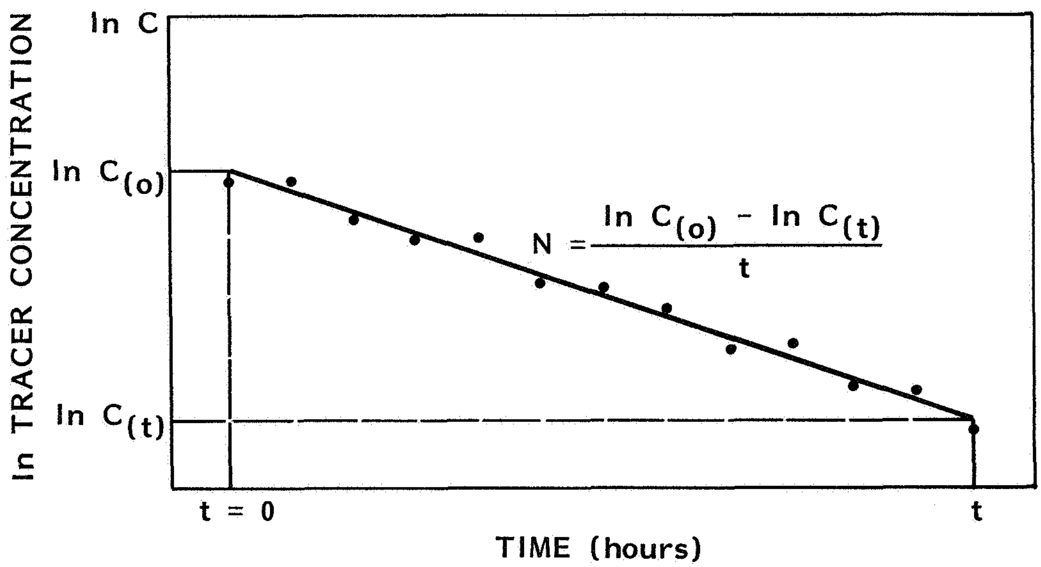

Figure 2.1.1 Logarithmic plot of decay rate data

Practical considerations

This method is often considered to be one of the most straightforward of all tracer gas techniques and was one of the first measurement methods to be used by air infiltration research workers, e.g. Dick [1950]. With the development of more sophisticated air flow rate measurement techniques the use of the decay rate method has declined. However many of the problems associated with tracer gas measurements were first encountered and solved whilst applying the decay rate technique. These solutions are often equally applicable to other tracer techniques. For this reason, and the fact that basic decay rate measurements can be made with a minimum amount of equipment, the decay rate method will be considered in detail here.

There are two slightly different approaches to the production of tracer concentration decay data. One type of technique requires the equipment used to analyse the tracer concentration to be placed in the measurement building (site analysis). A second type of technique involves taking samples of air in the measurement building and removing them to another site for analysis (grab sampling). These methods are considered below.

Site analysis

In its basic form, the site analysis technique for concentration decay measurements requires the following equipment:

- a tracer gas and a means of injecting it into the test space. (See Section 4.1 for further details about Tracer Gases)

- a means of mixing the gas into the test space in order to obtain an initial uniform concentration of tracer.

- an analyser which can detect the tracer gas in the concentrations used for the test. (See Section 4.2 for further details about gas analysers)

- a sampling system whereby a quantity of air from the test space can be introduced into the gas analyser.

- some means of recording time.

Figure 2.1.2 shows a schematic view of the decay measurement equipment. A tracer can be injected from the nozzle of a gas cylinder. This, however, is unlikely to produce a uniform concentration throughout the test space, and the actual quantity of gas injected is hard to control. Several systems have been used to overcome these basic problems. The tracer gas can be fed through a system of hoses which discharge the tracer at many points simultaneously. This system may only be suitable for long term test sites where tubing can be installed permanently.

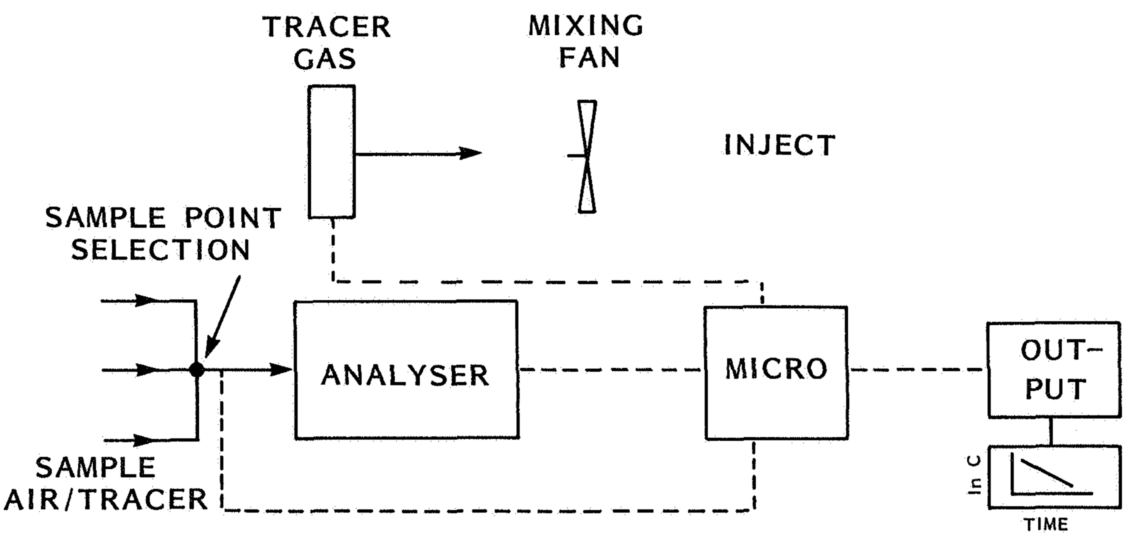

Figure 2.1.2 Schematic of tracer decay rate equipment (microcomputer optional)

Alternatively, gas can be injected into the space using, for example, a balloon or plastic bottle. The air is then artificially mixed by small fans. Oscillating desk fans are often used for this purpose. Care must be taken when using this system because artificial agitation of the air in the test space can, to some extent, alter the natural conditions which are to be measured. It is therefore advisable to cease artificial mixing before the monitoring of the tracer concentration commences.

The gas analyser can be located within the building or can be placed at a semi-remote site and connected to the building by tubing. Several analysers contain their own pump and sampling system; otherwise a small external pump may have to be used to draw air through the analysers. By connecting the analyser to sample tubing, the tracer concentration may be measured at any point within the test space. As mixing between air and tracer within the building will never be perfect (see Section 2.1.4), measurements made at a single point may not be indicative of the test space as a whole. The mixing problem can never be completely overcome. However there are measurement procedures which can go some way towards minimising the effect of non-perfect mixing. Air collected at a number of points can be physically mixed together in a chamber placed between the sample points and the gas analyser. The concentration of the mixture is then taken to be representative of the test space. Alternatively, it can be recognised that the tracer gas in various parts of a space will exhibit differing decay characteristics. Thus by introducing a system of valves between the sample tubes and the analyser, each location can be sampled in turn.

Gas analysers can usually be configured to give some form of analogue output, e.g. voltage, which is proportional to the concentration of the tracer gas. In the simplest form of decay rate measurement this output is connected to a chart recorder which contains a time base facility. Hence an instantaneous graph of tracer gas concentration against time is obtained. This data can then be manually manipulated to obtain a value of the air change rate (See Figure 2.1.1 and Equation 2.1.6).

The time taken to perform a single decay test will depend upon the air change rate and the detection limit of the tracer gas. The greater the air change rate, the sooner the tracer will approach a concentration where it is no longer detectable. Also the decay analysis assumes that the air change rate remains constant over the whole period of measurement. Air change rates are influenced by the fluctuating parameters of wind speed and temperature, so it is unwise to assume that they will remain constant over any great length of time. Hence, in a compromise with the need to obtain enough data to calculate a realistic estimate of the air change rate, single decay measurements are often about one hour in duration. The determined value of air change rate represents the average over the measurement period.

Even with associated measurements of wind speed and temperature, one value of the air change rate provides little information regarding the ventilation behaviour of the building. Ideally a series of measurements should be made, preferably under a range of climatic conditions. In order to ease this process, several refinements can be made to the basic system. The gas injection process can be automated so that, once the concentration has reached a certain minimum level, a further amount of tracer is injected into the test space. This allows many individual decays to be obtained. If more than one sample point is being used the automatic switching between each location can be performed with solenoid valves.

For analysis purposes the voltage output of the analyser can be fed into a computer or data logger and this, together with the associated software, is used to calculate and output the air change rate directly. Figure 2.1.3 shows the output from a system which illustrates two of these features.

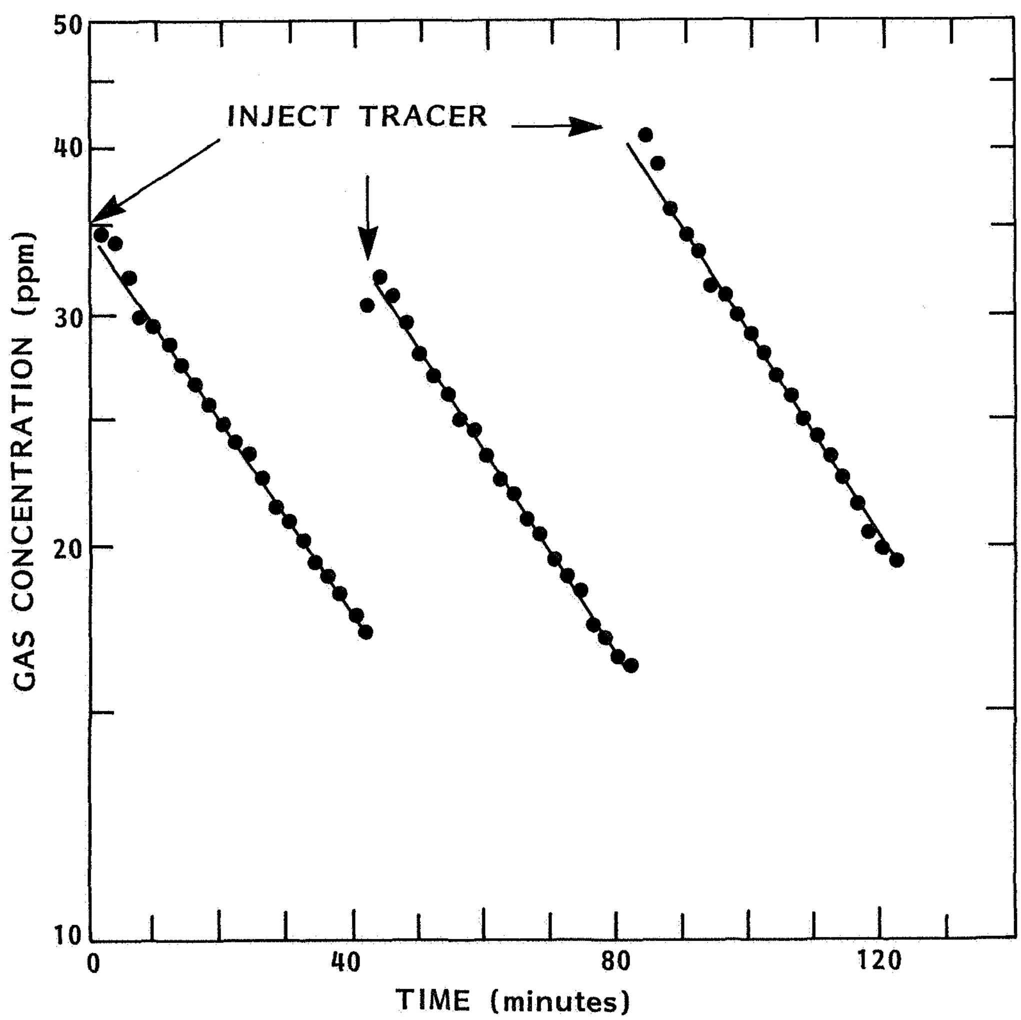

Figure 2.1.3 **Output from automatic decay rate measurement device (after CONDON et al [1980])**

Firstly the tracer gas injection is automatically pulsed so that several consecutive decays can be obtained, and secondly the decay rates are plotted on semi-log paper in order that the air change rate can be evaluated directly from the slope of the line.

Further information about basic decay rate measurements can be found in Section 6.1.

Grab sampling

This technique requires no expensive equipment to be used on the measurement site. The tracer gas is initially injected into the space and allowed to mix with the air. Because this whole process is designed to be as simple as possible, rudimentary injection techniques are usually employed: slowly releasing the tracer from a syringe or plastic bottle has shown itself to be adequate for the purpose. An initial period of time is allowed to enable the tracer gas to reach a relatively uniform concentration throughout the building. The air in the space is then sampled. Air sampling can be performed using syringes, flexible bottles, air bags or detector tubes. The sample taken in this manner is intended to give an instantaneous picture of the tracer concentration at that time, hence the actual time taken to take the sample should be kept as short as possible. After further known periods of time, more samples can be taken. A minimum of two samples are required to evaluate the decay, but often more are taken to ensure accuracy. The sequence of events for grab sampling are illustrated in Figure 2.1.4. The time interval between samples or the absolute time they were taken must also be recorded. Air samples are then returned to the laboratory for analysis. Concentrations are determined, the decay plotted and the air change rate evaluated. In the case of detector tubes the gas concentration is determined directly by observation of the scale on the tube.

An advantage of grab sampling techniques is that non-technical personnel can perform the site tasks thus allowing laboratory trained staff to concentrate on the gas analysis procedures. Because it is kept at a central location, the analysis equipment is less likely to be damaged or go out of calibration. As only simple site equipment is required many buildings can be evaluated, often simultaneously, with little increase in costs. The main problem with the technique is that the results cannot be evaluated until some time after the site data is taken. Grab sampling may also be susceptible to unintentional errors by the non-technical site operators, or loss of samples in transit.

Further information about decay rate grab sampling techniques can be found in Sections 6.2 and 6.3.

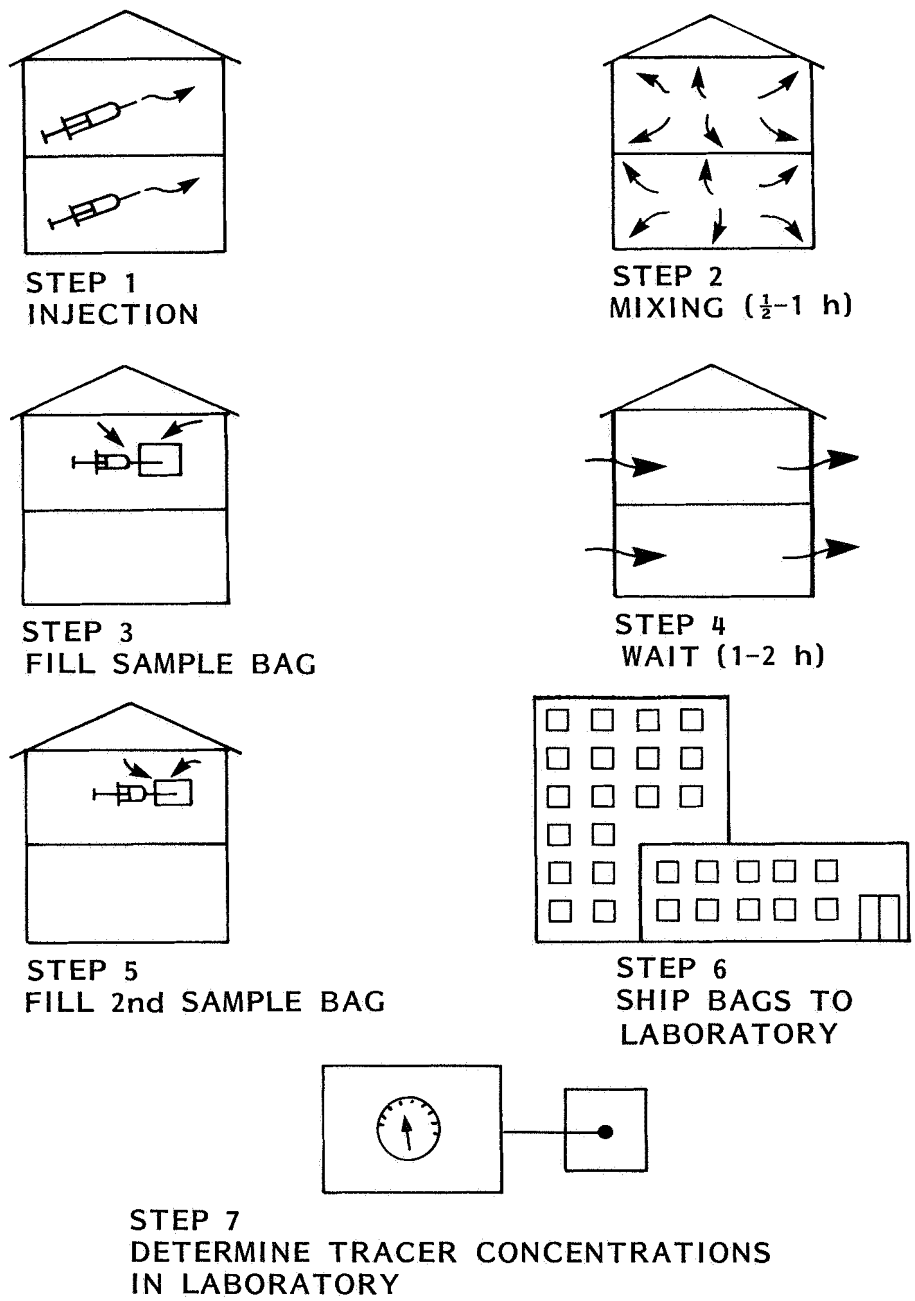

Figure 2.1.4 Decay rate - grab sampling events sequence (after GROT [1980])

2.1.2 Constant Emission Rate Method

Theoretical considerations

A second approach to the solution of the tracer gas continuity equation is to set the source term, not at zero but at some fixed value. This can be achieved, for example, by setting a gas cylinder to emit tracer at a uniform rate. Again, assuming the external tracer gas concentration to be zero, the continuity equation is given by:

$$V \frac{dC}{dt} = -QC_{(t)} + F \qquad [2.1.7]$$

This can be solved in terms of the concentration of tracer gas within the enclosure:

$$C_{(t)} = \frac{F}{Q} + \left[C_{(0)} - \frac{F}{Q}\right] e^{-\frac{Q}{V}t} \qquad [2.1.8]$$

If the air flow in and out of the enclosure remains constant and there is no tracer present before the start of the test, Equation 2.1.8 becomes:

$$C_{(t)} = \frac{F}{Q}\left[1 - e^{-Nt}\right] \qquad [2.1.9]$$

Where

Q = Specific air flow rate through enclosure, m^3s^{-1}

$N = \frac{Q}{V}$ = Air change rate per unit time

If N remains constant, a finite time is required for the tracer concentration to reach equilibrium. This time is determined by the bracketed function in Equation 2.1.9 (see Figure 2.1.5). Once the concentration has reached equilibrium, the air flow rate is given by

$$Q = \frac{F}{C_{(t)}} \qquad [2.1.10]$$

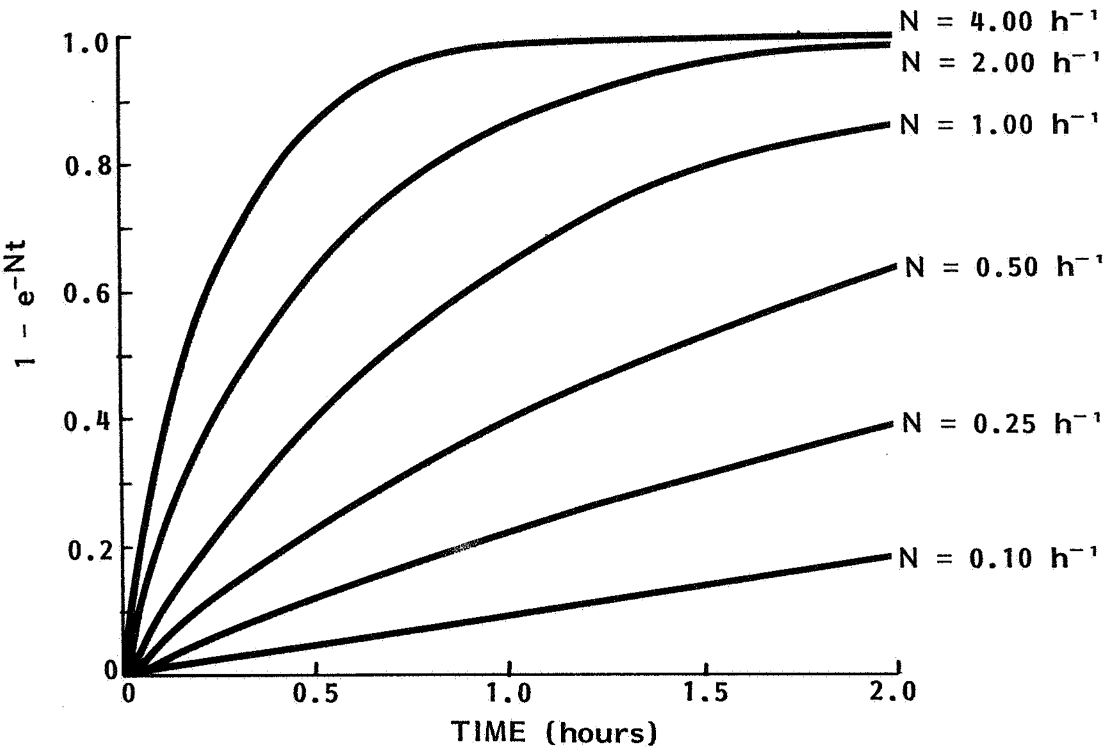

Figure 2.1.5 $(1 - e^{-Nt})$ as a function of time for various values of N

So by setting the tracer flow rate to an appropriate value and monitoring the concentration within the enclosure, the value of the specific air flow rate into the building can be determined. Alternatively, if the air flow rate is not constant with time, then neither will be the tracer concentration. However over short sampling periods (typically 15 min) the average specific air flow rate can be determined from the average tracer concentration. These values of air flow rate can be determined without a knowledge of the building volume. In some cases this is an advantage especially where the building volume is difficult to determine (see Section 2.1.4). If the results are to be expressed in terms of air change rate then the volume of the building must be evaluated.

Practical considerations

This technique requires tracer gas to be injected into a building at a known and constant rate. Similar to the decay method, there are two basic sub-groupings of the constant emission technique: those which require the gas analysis equipment to be on site and those in which the gas analysis equipment can be placed at a central location.

Site analysis

In these techniques, all the equipment used for the test is placed in the building to be examined. The essentials of the measurement technique are similar to the decay method except that the tracer is injected continuously over the measurement period. In order to aid mixing, the gas may be injected from a tube, the mouth of which is placed near a small mixing fan. Prior to monitoring it may be necessary to spend some time injecting gas into the test space in order that approximate equilibrium conditions may be reached. Once the transient effect (see Equation 2.1.9) has become minimal, for the case of constant ventilation rate, the air change rate becomes inversely proportional to the tracer gas concentration in the test space, i.e., the lower the gas concentration, the higher the air change rate.

In order to determine the air change rate it is necessary to measure, control or know the tracer gas injection rate, and to measure the concentration of tracer in the building. This type of measurement is usually performed with fully automated equipment which is controlled by a microcomputer. A schematic of the constant emission rate equipment is shown in Figure 2.1.6.

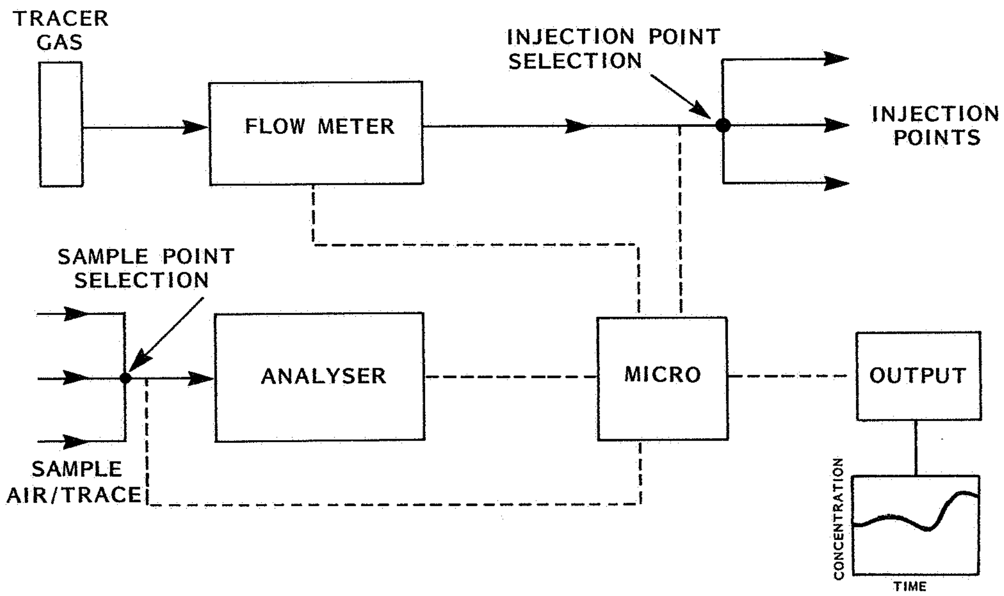

Figure 2.1.6 Schematic of constant emission rate equipment

The tracer concentration is measured either continuously or at short intervals, thus essentially allowing continuous measurements of the air change rate to be made. As with the decay technique, samples may be taken from several locations. Associated with the advantage of obtaining continuously variable air change rate data is the disadvantage of using large quantities of tracer gas. A careful choice of tracer gas and required concentration levels can reduce the problem of high tracer gas consumption and costs to a minimum (Dietz [1988]).

Averaging techniques

An alternative to having all the analysis equipment on site is to have only the gas injection and sampling systems in the building. Gas is injected at a constant rate into the test space. This can be achieved by using a gas cylinder with a needle valve which can be set to give the appropriate flow rate, by using a passive permeation source which emits tracer at a rate influenced only by temperature, (Dietz [1986]) or by utilising a leak proof gas bag equipped with a small pump.

For short-term tests the air in the test space can be collected in any whole air sampling device (e.g., syringe, sample bag with pump or canister). Air is drawn into the device over a given period of time and therefore represents a time average of conditions within the space.

The sample device is then removed and the concentration of tracer gas is determined in a laboratory. From this determination, and the known flow rate of tracer gas into the room, the average air change rate over the time monitored can be evaluated from the average tracer gas concentration data. In order to increase the accuracy of such measurements, several sample devices may be used to collect air from different parts of the building.

The advantage of short-term averaging measurements is that the expensive and highly technical analytical and calculational equipment does not have to be brought into the building and yet variable air flow rates can still be quantified; a disadvantage is that the flow information is not available in real-time.

To avoid having to use expensive tracer release and sampling equipment, a further long-term monitoring technique has been developed. The only site equipment required for this technique are the passive gas emitters and passive tracer samplers. Emitters are about 30 mm long and samplers about 70 mm long, each has a diameter of about 5 mm. One emits gas at a constant rate (there is a slight temperature dependence), and the other samples tracer gas by the principle of passive diffusion. The time-averaged tracer concentration is determined from analysis of the sample tubes in a central laboratory. The effective ventilation rate is evaluated from Equation 2.1.10. Further details of this technique are presented in Section 6.4.

The main advantage of the long-term passive system is that emitters and samplers can be placed in a building by non-technical personnel and mailed back to the laboratory when the test is complete. A disadvantage with long-term measurements is that although they accurately determine the average effective ventilation rate (useful for indoor air quality purposes), under conditions of variable air change rate, the actual air flow rate is always higher than that evaluated. Under conditions of highly variable air change rate (greater than ± 100%), the negative bias can exceed 50%. This problem is addressed further in Section 6.4.

Occupant generated carbon dioxide method

The air change rate of an occupied space can be evaluated by monitoring internal and external carbon dioxide concentrations. People constantly breath out carbon dioxide and hence act as the source term in the tracer gas continuity equation (Equation 2.1.1). The external concentration of carbon dioxide is not zero so, in this case, the continuity equation cannot be further simplified. If however, individual carbon dioxide production rates and the number of occupants are known, or can be measured, then the air change rate can be evaluated (see, for example, Penman [1980]).

There are two main difficulties with this approach. Firstly carbon dioxide production rates vary from person to person, and an individual's production rate is very dependent upon their activity level. This implies that this method is actually based on continuous but variable emission rather than constant emission rate theory. Secondly, unless all the air entering the space is from outside (i.e., no air entering from other internal spaces), there may be some difficulty in estimating the carbon dioxide concentration of the incoming air. A refined analysis for this technique, designed to overcome these problems, has been presented by Penman and Rashid [1982]. Carbon dioxide concentrations can be measured with an infra-red gas analyser (see Section 4.2.1), and occupant levels can be obtained by visual inspection.

Whilst not widely used, this technique has been utilised in both naturally and mechanically ventilated buildings with satisfactory results (Penman [1980] and Penman and Rashid [1982]). These authors state that this method may be ideal for long-term studies in occupied buildings. Particularly if objections to breathing a tracer gas in the air over a prolonged period of time have been raised by, or on behalf of, the occupants.

2.1.3 Constant Concentration Method

Theoretical considerations

A third approach immediately reduces the continuity equation to its simplest form. If the concentration of tracer gas within the enclosure is maintained at a constant level, then there is no rate change in tracer and the continuity equation becomes Equation 2.1.11.

$$F_{(t)} - QC = 0 \qquad [2.1.11]$$

Where

$F_{(t)}$ = Production rate of tracer at time t

Equation 2.1.11 can be solved to give:

$$Q = \frac{F_{(t)}}{C} \qquad [2.1.12]$$

Where

Q = Specific air flow rate through enclosure, m^3s^{-1}

This is exactly the same expression as used for the constant emission rate method, only here the variable quantity is the tracer gas production rate. The air change rate is directly proportional to the tracer gas injection rate required to maintain the concentration. As with the constant emission rate method the specific air flow can be determined without knowledge of the building volume. If the results are to be expressed in terms of air change rate, then this building volume must be evaluated.

Practical considerations

The practical realization of this simplified theory presented above is the most demanding, in terms of equipment and expertise, of all the air change measurement methods. The aim is to maintain the concentration of a tracer gas at a given level throughout the whole enclosure. By periodically sampling the tracer gas concentration, it is possible to determine the amount of tracer which must be injected to maintain the concentration at the required level. The amount of tracer injected is directly proportional to the air change rate of the test area, i.e. the more tracer required to maintain the concentration the higher the air change rate. With a short time interval between air sampling and gas injection it is possible to obtain continuous measurements of the air change rate.

Because of this essential feedback between concentration and injection, the constant concentration technique requires a sophisticated control mechanism. Fully automated instrument packages, incorporating a microcomputer, have been designed for this purpose (see Figure 2.1.7). Using these packages the concentration can be kept constant in several zones of the test building thus enabling the air change rate of individual rooms to be evaluated. The major advantage of these systems is that, being fully automated, they can be left unattended in the measurement building and they will still gather data, usually storing it on computer disk. Very sophisticated systems will allow an operator to contact the microcomputer from any distance via a standard telephone line connection.

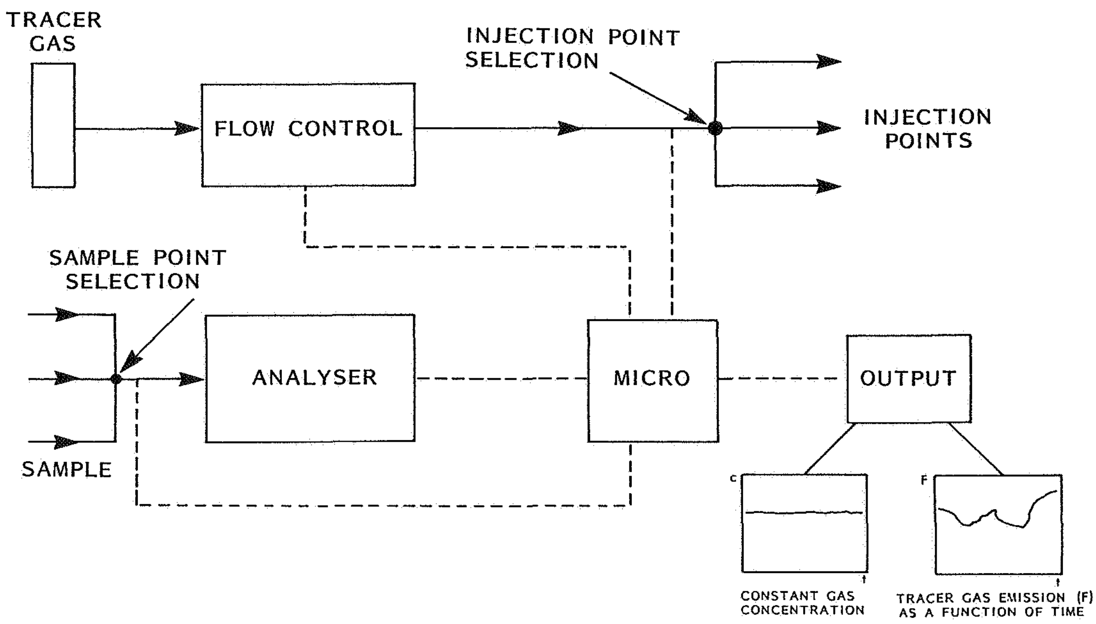

Figure 2.1.7 Schematic of constant concentration equipment

Further details about the equipment required to perform constant concentration tracer gas measurements can be found in Section 6.5.

2.1.4 Mixing and Effective Volume

The continuity equation is derived under the assumption that the ventilation air and tracer are perfectly mixed. If this assumption is correct, then at any instant the tracer gas concentration will be constant throughout the whole measurement space. In real buildings, this is rarely the case, and at any instant the tracer concentrations will vary from point to point.

One measurement method designed to overcome this problem is to measure the tracer gas concentration at several locations and to assume that the mean of these values is representative of the average concentration in the test space. Whilst this goes some way towards overcoming the problem, the factors which affect the mixing of air and tracer cannot be ignored.

Three different types of mixing problem can be identified: mixing of the ventilation air into the enclosure, mixing of tracer gas into the enclosure and circulation of air and tracer within the enclosure.

Mixing ventilation air into the enclosure

When outdoor air enters an enclosure through a variety of leakage paths, it may not disperse evenly throughout the space. In reality the mixing action of the outdoor air and indoor air will lie somewhere between the limits of perfect instantaneous and homogeneous mixing and no mixing at all. In extreme cases the outdoor air can bypass the indoor air without mixing with the main volume of the room. This is often referred to as short circuiting. Outdoor air can propel the internal air before it like a front. This can result in piston or displacement flow. Figure 2.1.8 illustrates the four main types of air flow pattern found in the ventilated space.

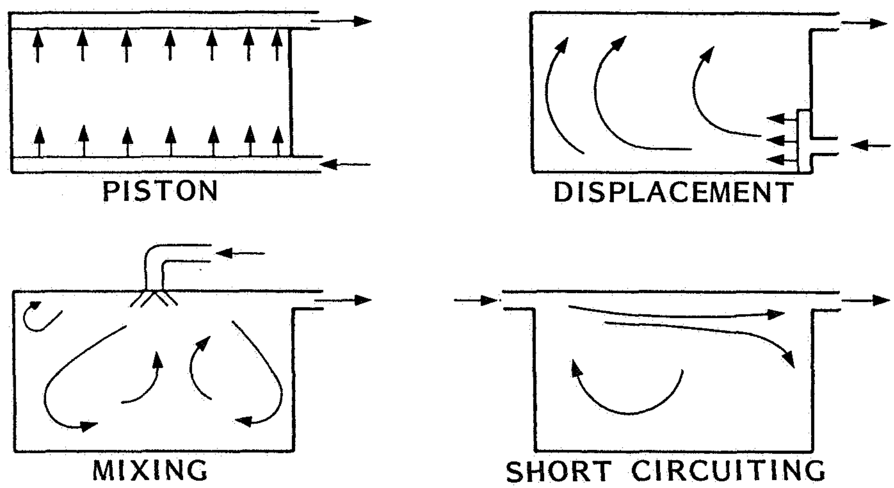

Figure 2.1.8 Four types of air flow pattern in the ventilated space (after IEA ANNEX IX, [1987])

During tracer gas measurements it is poor mixing of the outdoor air which causes spatial variations of tracer gas concentration to occur. In a house, for example, the concentration can vary from room to room, leakier rooms having lower concentrations than tighter. In larger enclosures such as industrial buildings, the instantaneous concentration may vary widely within a single space. These variations may, of course, imply that the air change rate is not uniform throughout the test enclosure. With this type of building or compartmentalized buildings such as apartment blocks, it may be necessary to utilise a multi-chamber approach in order for measurements to be properly analysed. Measurement of interzonal air flow in compartmentalized buildings is examined in Section 2.2.

Mixing tracer gas into the enclosure

A second mixing problem occurs with the injection of the tracer gas. In some measurement techniques, gas injection and sample points are located some distance apart. Therefore there is a delay between the time a volume of tracer is injected and the time the additional volume is reflected in the sampled concentration. Injection mixing problems are often reduced by the use of small electric fans. These are placed at the injection points so as to promote the mixing of the gas into the indoor air. Care must be taken, however, to ensure that these fans do not induce artificial flow conditions within the test space. This can be done by using small fans especially designed for the purpose, or by switching off the fans after an initial period of vigorous mixing has occurred. In some cases it may be possible to use the air handling system to mix the tracer gas throughout the building.

Mixing air and tracer within the enclosure

It can be seen from Equation 2.1.1 that the volume used in the continuity equation is the effective volume. This is defined as the volume in which mixing occurs and it is not necessarily equivalent to the physical volume of the enclosure. The presence of cupboards and furniture, for example, can lead to the effective volume being smaller than the physical volume. These volumes can often be readily identified and allowed for. Alternatively their effect can be nullified by opening them to the main space. However, there may be other "dead" volumes such as areas near the ceiling or floor, isolated by stratification, which are more difficult to evaluate. This effect is illustrated as short circuiting in Figure 2.1.8. If there are attached spaces which can communicate with the measured enclosure, then the effective volume may be larger than the obvious physical volume. An example of this would be a suspended ceiling above a living space (see Figure 2.1.9). Whilst it is often usual to assume that the effective volume will be approximately the same size as the physical volume, a careful examination of the building will lead to a more accurate evaluation of this parameter.

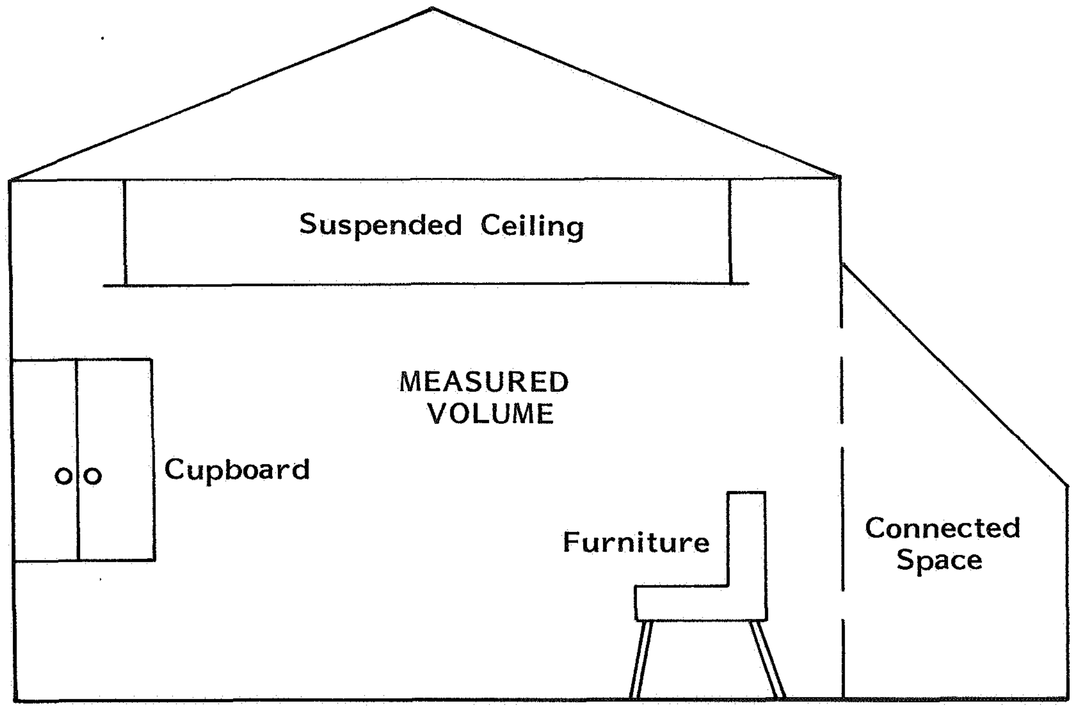

Figure 2.1.9 Schematic of several factors affecting effective volume

2.2 MEASUREMENT OF INTERNAL AIR EXCHANGE RATES

The continuity equation derived in Section 2.1 assumes that the test space under consideration is a single, well mixed enclosure (see Section 2.1.4 for a discussion of this assumption). This is adequate, in many cases, to enable the specific air flow into a space to be evaluated using tracer gas techniques. Recently, air flow between internal spaces and air exchange between the external environment and individual internal spaces has come under examination. Interzonal air movement is important when considering the migration of pollutants from one area of a building to another. For example if moisture which is produced in kitchens or bathrooms is transported to other, colder areas of a dwelling, then condensation problems may occur.

2.2.1 Theory of Interzonal Air Flow Measurement

Measurement of these interzonal air flows and individual zone air change rates involves the use of tracer gas methods. The starting point for the analysis of these techniques is the tracer gas continuity equation. The structure under consideration is assumed to consist of a number of physical cells in each of which air and tracer are perfectly mixed. For these purposes the minimum number of cells required to describe the building will depend, among other things, on how the internal doors are set. In a dwelling where all the internal doors are open the number of cells, n, may be as low as two (basement and rest of house), but if some doors are closed then n may have to be higher. If there are n cells then these may be labelled cell 1, cell 2 .....cell n and, for i = 1 to n, the volume of the i'th cell is V_i. A tracer mass balance equation can be developed for each cell. In this case, as well as the exchange with the environment, the tracer lost to, and gained from, each of the other cells in the building must be taken into account. If the concentration of the tracer in the atmosphere is taken to be zero, then the continuity equation for the i'th cell is given by

$$V_i \frac{dC_i}{dt} = F_i + \left[\sum_{j=1}^{n} Q_{ji} C_j (1 - \delta_{ij}) \right] - \left[Q_{ie} C_i + \sum_{j=1}^{n} Q_{ij} C_i (1 - \delta_{ij}) \right] \qquad [2.2.1]$$

Where:

V_i = Effective volume of cell, i., m^3

C_i = Tracer gas concentration in cell, i, at time, t

F_i = Production rate of tracer in cell, i

Q_{ij}/Q_{ji} = Volume flow rate of air between cells i and j. Q_{ij} indicates flow from cell i to cell j, Q_{ij} and Q_{ji} are not necessarily equal

Q_{ie} = Air flow from cell, i, to the outdoor environment, m^3s^{-1}

The delta function is:

$\delta_{ij} = 0$, when $i \neq j$

$\delta_{ij} = 1$, when $i = j$

Since there is no net build-up of air in the building, the total flow into a cell must equal the total flow out. Therefore a second set of n equations can be obtained by considering the mass conservation of air. So for each i'th cell the rate of air flow in equals the rate of air flow out. This is expressed by Equation 2.2.2.

$$Q_{ei} + \sum_{j=1}^{n} Q_{ji}(1-\delta_{ij}) = Q_{ie} + \sum_{j=1}^{n} Q_{ij}(1-\delta_{ij}) \qquad [2.2.2]$$

Where:

Q_{ei} = Air flow from the outdoor environment into cell i, m^3s^{-1}

The task here is to determine the interzone air flows, i.e. the Q_{ij}'s. This can be achieved by making site measurements of tracer gas concentrations in the cells. There are (n^2-n) unknown interzonal air flows plus the 2n unknown values of Q_{ie} and Q_{ei}, giving a total of (n^2+n) unknown values of air flow. There are n equations from Equation 2.2.1 plus n equations from Equation 2.2.2. If the n equations of Equation 2.2.1 are used then there are still n^2 unknown air flows with only the n equations from Equation 2.2.2 left to solve them. Therefore (n-1) independent sets of equations similar to Equation 2.2.1 must be generated.

Solving Equations 2.2.1 and 2.2.2 to obtain values of the interzonal air flows is beyond the scope of this document (see, for example, Sinden [1978]). However, there are three suggested methods by which the required (n-1) equations could be generated.

i) Using continuous tracer emission (see Section 2.1.2) with the injection rate being varied n times.

ii) Observing C_i and dC_i/dt at n different time points

iii) Using n different tracer gases.

Methods i) and ii) imply the use of a single tracer gas and measurements of this type have been performed, e.g. Grimsrud [1979].

The use of these methods greatly increases the duration of a test run, and the assumption that the Q_{ij}'s remain constant over this period is dubious. It is simpler to use n different gases to give the required n^2 equations than to increase the measurement period. This ensures that changes in external weather conditions do not violate too strongly the time invariancy of the interzonal air flows.

The complex dependency of multizone air flow on the n concentration measurements can lead to unstable solutions, in which the uncertainty associated with many of the determined flow rates can be very large. A proper error analysis is essential in all multizone flow determinations (see for example D'Ottavio et al [1988]).

Air flows between internal spaces are almost always measured using multiple tracer gas techniques.

2.2.2 Practice of Interzonal Air Flow Measurement

Measurement of the rate of air flow between the interconnected spaces of a compartmentalised building is generally performed using multiple tracer gas techniques. Several such methods have been developed and each is essentially an extension of one of the single tracer gas techniques described in Sections 2.1.1 - 2.1.3. These techniques are examined below.

Multi-tracer decay

By extending the single zone decay rate technique described in Section 2.1.1 measurements of interzonal air flows can be made. If the building is divided into a number of distinguishable zones, then the same number of gases as zones must be used to make the measurements. A separate gas is released in each zone and in order to evaluate the air flows the concentration of all gases must be monitored in each zone. The measurement equipment should be portable and not much more complex than its single gas counterpart. In order to achieve this it must be possible to distinguish and analyse, in terms of concentration, each individual gas using a single detector. Several "families" of tracer gases exist which in conjunction with the correct detector, can be used for this purpose. Tracer gases and detectors are discussed in further detail in Sections 4.1 and 4.2 respectively.

The aim of this type of measurement is to evaluate the instantaneous rate of air flow between the various internal spaces of a building under a specific set of environmental and building usage conditions. Environmental conditions in particular are prone to rapid and uncontrollable variation. It is therefore advisable to obtain values for the air flows in as short a time as possible.

Several practical multi-tracer decay measurement systems have been developed, for example, Irwin [1985] or Prior [1985]. Essentially the tracer gases are released one to each cell and mixed with the indoor air using small mixing fans. These fans are only used for a short time and are turned off before tracer concentration measurements are made. This ensures that artificial flow conditions are not introduced during the period of the measurement. Air/tracer samples are drawn from each zone and analysed in terms of tracer concentration. The measured time and concentration points are then used to evaluate the interzonal air flows. Details of a multi-tracer decay system designed to evaluate the air flow rates between three distinguishable cells are presented in Section 6.6.

Multi-tracer constant emission

Measurements of the air exchange rates between zones in a building can be made by the constant emission method using an extension of the passive sampling technique noted in Section 2.1.2. In this case a separate source of tracer is placed in each zone. Currently seven distinguishable perfluorocarbon tracer sources are available, and five can be used simultaneously.

A single sample tube placed in each zone will collect samples of each of the gases released in the building. At the end of the measurement period sample tubes may be removed and analysed in a laboratory. Tracer concentrations are determined and with this information plus a knowledge of the emission rates of the tracer sources in each zone, the air exchange rates between zones can be evaluated. Further details of the passive PFT sampling technique can be found in Section 6.4.

Multi-tracer constant concentration

Continuous interzonal air flow measurements can be made with an extension of the single tracer gas constant concentration technique as described in Section 2.1.3. In this technique a separate gas is injected into each zone of the measurement building. Tracer gas injection and monitoring equipment is used to maintain a constant concentration of each tracer gas in the zone where it is injected. It is not possible to maintain a constant concentration of the tracer gases in the zones where they are not injected. Therefore, the concentration of each tracer is monitored in each zone of the measurement building. This data is used to evaluate the air flow rate between the zones.

This technique is intended to continuously monitor individual zone air change rate and the air flow rates between zones. Therefore rapid tracer gas analysis methods and sophisticated control techniques must be utilized in this measurement method.

2.3 PRESENTATION OF AIR EXCHANGE RATE MEASUREMENT RESULTS

Measurement techniques evaluate air exchange rates under prevailing conditions. Some techniques produce only discrete values of air change rate or interzonal air flows. If presented on their own these values will provide little information about the ventilation behaviour of the building. This is due to the fact that air flow rates are themselves variable parameters depending upon a variety of constructional, climatic and behavioural factors. Thus, when presenting air flow rate values, some information regarding the building, ventilation system, climate and occupancy must also be provided.

A guideline to the minimum additional information required to enable adequate interpretation of air flow rate data is given below.

Building

Type, construction, volume, state of openable apertures such as doors and windows.

Ventilation System

Type, size, condition e.g., inlets/outlets, open/closed.

Climate

Wind speed, wind direction, internal and external temperature.

Occupants

Number, behaviour, interaction with ventilation systems.

A detailed account of the information required for result presentation is given by Allen [1981]. One method of presenting discrete flow rate measurement results is shown in Figure 2.3.1. Here flow rate values are combined with weather and building data to provide an instantaneous picture of the ventilation behaviour of the building.

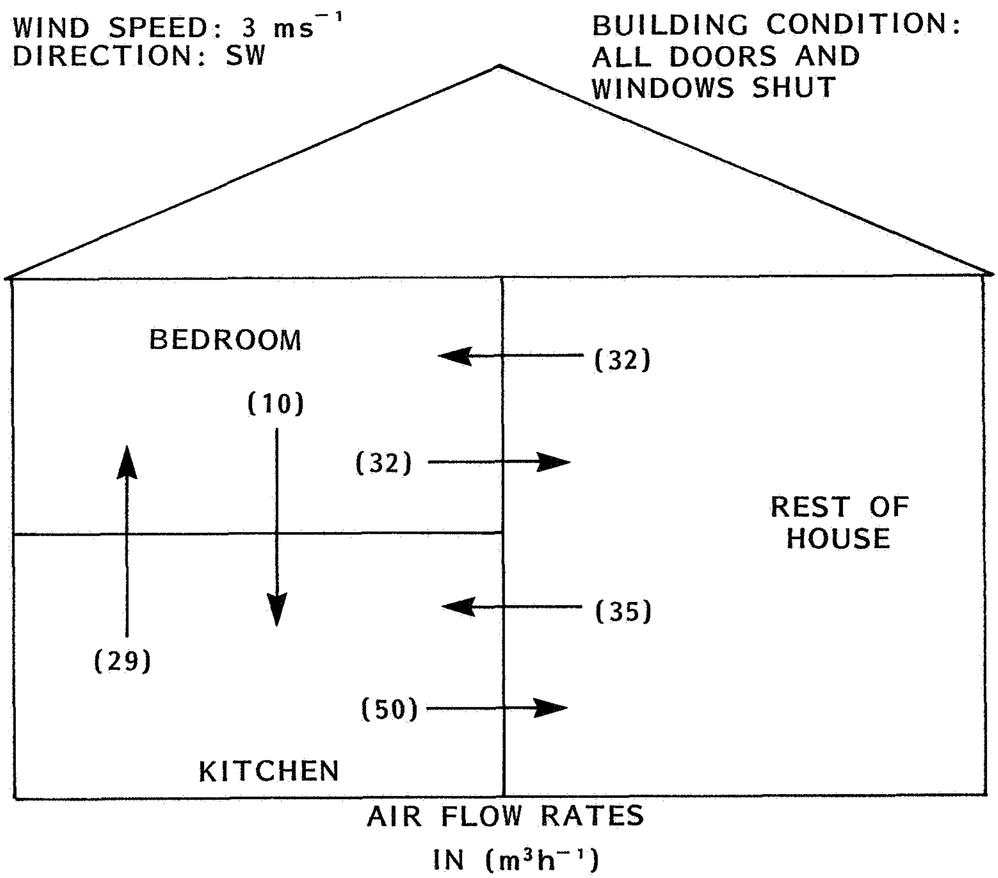

Figure 2.3.1 **Example of interzonal air flow rate measurement presentation (after IRWIN [1985])**

Some measurement techniques can provide a constant output of air flow rate data. In these cases a chronological record of flow rate values can be presented. Again, however, building, climatic and behavioural parameters must be presented in order to gain maximum information from this data. Figure 2.3.2 shows an example of this type of presentation. Along with air change rate and time; wind velocity and direction, external temperature and the state of windows and ventilation system are presented. From this type of graph the relative effect of various factors, on flow rate, can be assessed.

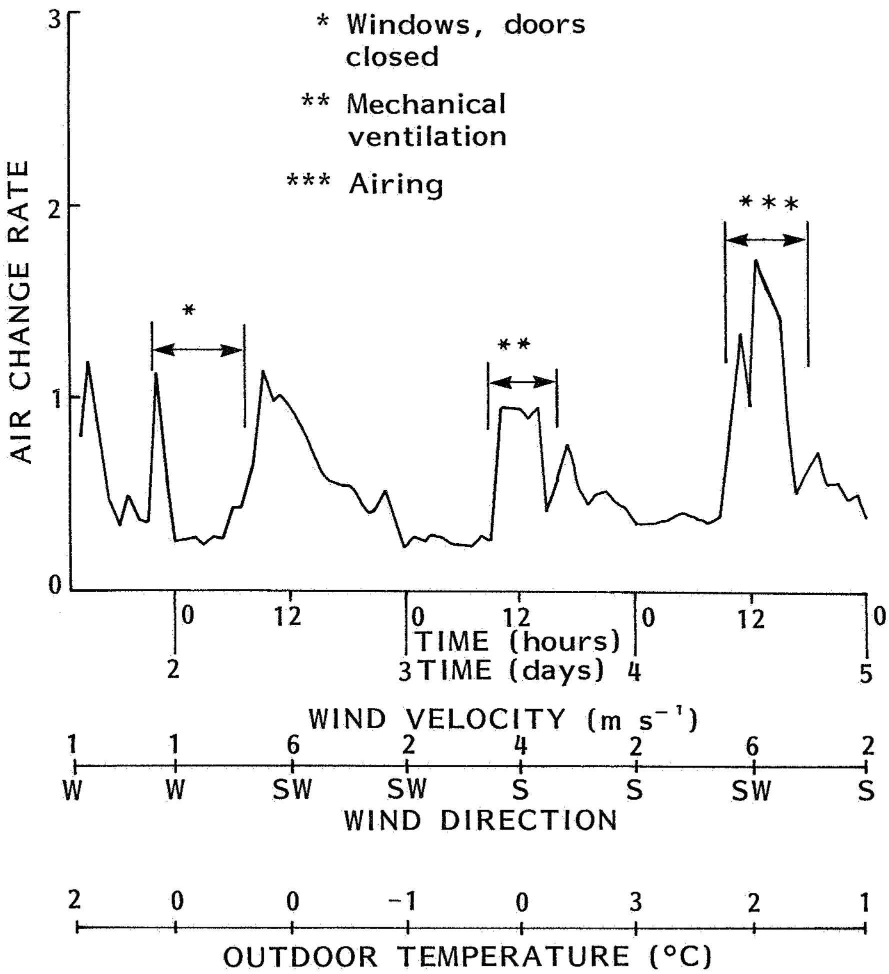

Figure 2.3.2 Example of continuous air change rate measurement presentation (after KVISGAARD et al [1985])

When long-term monitoring is undertaken (this may consist of making several discrete evaluations or one continuous measurement of variable air flow rate(s)), then functional relationships between parameters may be developed. A schematic of this type of presentation is shown in Figure 2.3.3. This illustrates the general infiltration characteristics of a building showing the effect of wind and temperature.

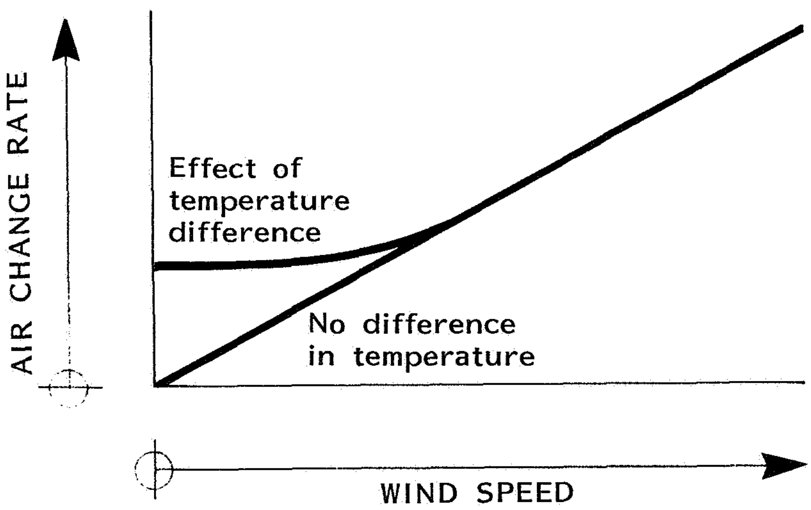

Figure 2.3.3 **Schematic of infiltration characteristic presentation**

These examples of result presentation may not be equally applicable to all measurement techniques. Information regarding the presentation of results from individual techniques is presented in Chapter 6.

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CHAPTER 3: Measurement of Airtightness

CHAPTER 3 MEASUREMENT OF AIRTIGHTNESS

This chapter examines the fundamental theory and practice of evaluating building envelope and building component airtightness.

The main reason for conducting building airtightness measurements is to characterize the building fabric without climatic or other variable parameters influencing the results. The practical aspects of conducting these types of tests are considered in Sections 3.1 and 3.2.

3.1 MEASUREMENT OF BUILDING ENVELOPE AIRTIGHTNESS

There are two basic approaches to the evaluation of building airtightness; DC pressurization and AC pressurization. The former technique has been in use for many years and currently measurements can be made in many types of building often using commercially available equipment (see Section 4.3).
DC pressurization is also the subject of several national standards (see Section 5.2). The second technique, AC pressurization, has been developed more recently. It has yet to be used extensively in field work but because of potential advantages it may have over DC pressurization, it too will be considered here.

3.1.1 DC Pressurization

External fan pressurization

The majority of measurements in this category have been performed in small residential buildings. The technique usually involves replacing an external door with a panel containing a powerful, variable speed fan. A correctly designed panel will not require the existing door to be removed from its hinges. Initially developed and used as a research tool, several commercial "blower doors" are now available (see Section 4.3). These can be adjusted to fit snugly into any domestic door frame. Air flow through the fan creates an artificial, uniform, static pressure within the building. Internal and external pressure taps are made and a manometer is used to measure the induced pressure differential across the building envelope. It has become common practice to test buildings up to a pressure difference of 50 Pa. Some means must also be provided to enable the volumetric flow rate through the fan to be evaluated. The aim of this type of measurement is to relate the pressure differential across the envelope to the air flow rate required to produce it. In general the higher the flow rate required to produce a given pressure difference, the less airtight the building. Quantitative methods of expressing airtightness results are examined in Section 3.3.

The air flow required to produce a given pressure difference under pressurization (air flow in) will not necessarily be identical to the flow required to produce the same pressure differential under depressurization (air flow out). This difference is due, in the main, to the fact that certain building elements can act as flap valves. For example, some types of window will be forced into their frames under pressurization while the reverse will be true for evacuation. This implies that the actual leakage area of the building envelope will be a function of the type of test conducted. Baker [1986] suggests that, in addition to this effect, the asymmetric geometry of some cracks with respect to the flow direction may explain significant changes in leakage characteristics with no associated change in leakage area. This type of crack may occur around casement windows where one leg of an L-shaped crack may be longer than the other. Hence, ideally, the fan and flow measuring mechanism must be reversible.

The general configuration for a pressurization/depressurization test is shown in Figure 3.1.1. The measurement procedure will depend upon the purpose of the test and the exact equipment used.

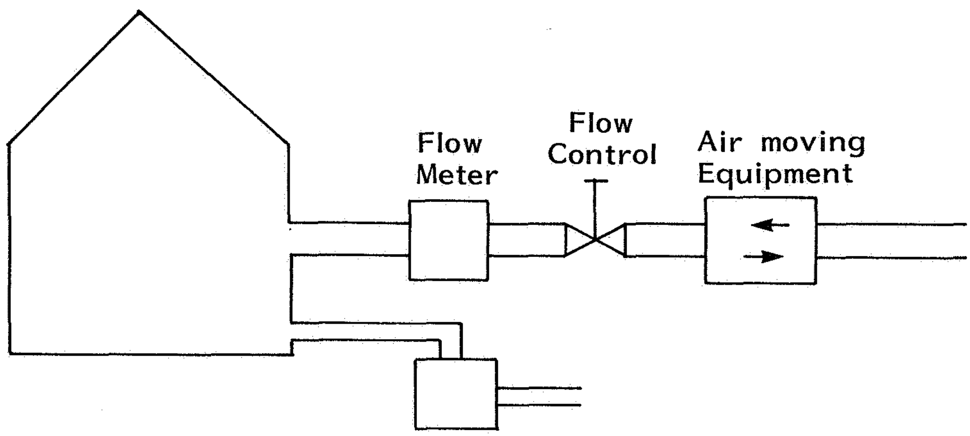


Figure 3.1.1 Schematic of whole building airtightness test (after ISO DP 9972 [1988])

Practical uses of whole house fan pressurization include the 'before' and 'after' testing of air sealing measures (retrofitting), the identification of leakage paths (usually in conjunction with thermography or smoke tests - See Section 3.4), and the evaluation of leakage path distribution through the envelope. By selectively sealing different potential leakage paths with, for example, plastic sheeting or sticky tape it is possible to determine the fraction of the total air leaking through different components of the building envelope. Further components can be sealed and pressurization tests performed accordingly. Hence this technique is often known as reductive sealing. As the components will be generally sealed from the inside for this type of test, it is preferable that an overpressure rather than an underpressure be created within the building. Pressurization will tend to force the seal onto the component while a negative pressure will tend to act against the seal making it less airtight.

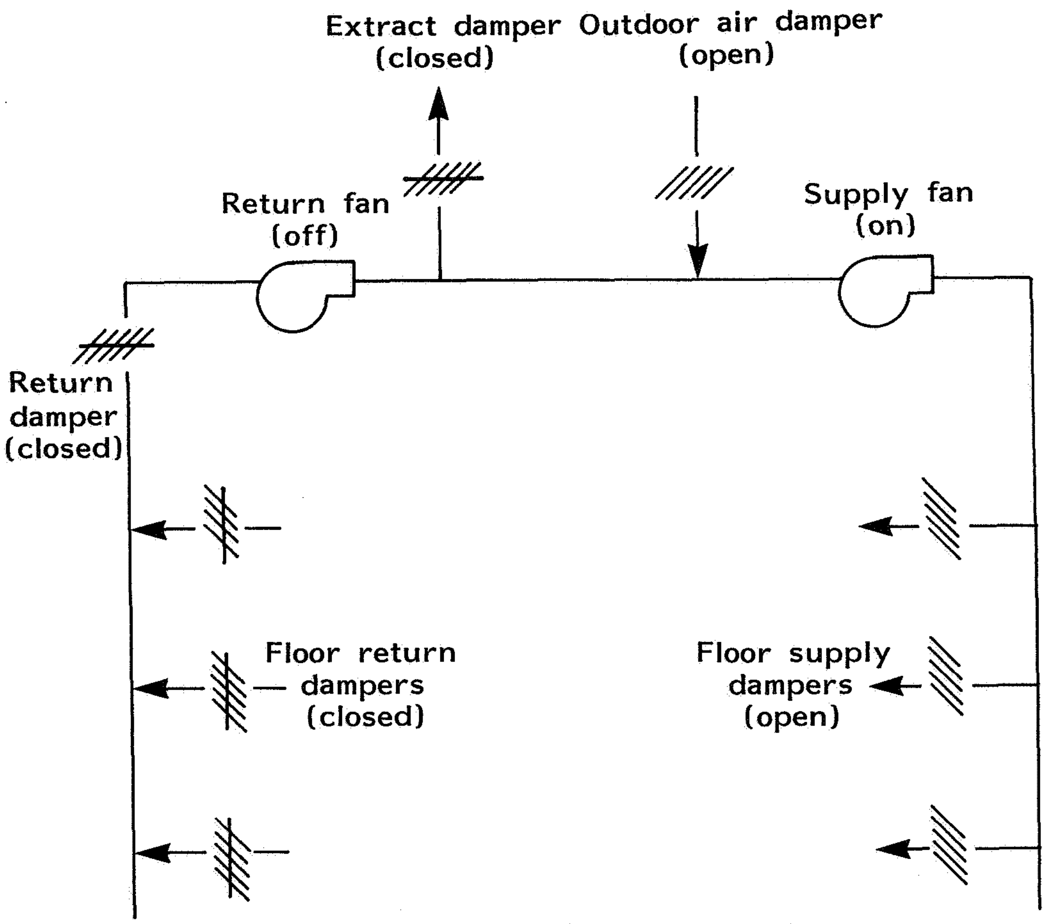
Theoretically there is no limit to the size of building which can be examined with DC pressurization. However, the maximum volume of enclosure which may be pressurized is governed by the overall airtightness of the structure and the size of the available fan. Even if large fans are available, in large leaky structures it may be possible to only achieve a limited range of pressure differentials. Several researchers have used trailer mounted fans with maximum flow capacities of about 25 m^3/s to examine buildings with volumes in the region of 50,000 m^3 (see, for example, Shaw [1981]).

<u>Internal fan pressurization</u>

Because of the size and cost of trailer mounted equipment and the inherent difficulties of transportation and required manpower, other techniques have been developed for the examination of large buildings. One method is to create the required pressure differential using the building's existing air handling system (see Figure 3.1.2). This technique relies on the building possessing a suitable mechanical ventilation system which can be adjusted to meet the needs of the measurement. Essentially, the supply fans are operated while all return and extract fans are turned off. All return dampers must be closed so that the air supplied to the building can only leave through the doors, windows and other leakage sites. Further details of this type of technique are provided in Section 6.8.

The analysis of these type of measurements proceeds along the same lines as that for small buildings, but because of the large building volume it may not be possible to achieve a pressure difference of 50 Pa. Persily [1986], for example compared the results of several building measurements by quoting the volume flow rate at a pressure difference of 25 Pa.

DC Pressurization is subject to the disturbing influence of natural pressure fluctuations created by the wind. Hence most measurements in a DC Pressurization test are made at pressure differentials far above those created by natural forces. This may lead to inaccuracy if the results are extrapolated to lower pressure differentials. A discussion on wind effect errors is presented in Section 6.7.6.



NOTE: State of fans and dampers during pressurization test conditions are shown in brackets.

Figure 3.1.2 Schematic of DC pressurization using internal fans (after PERSILY [1986])

3.1.2 AC Pressurization

AC Pressurization is a technique which allows building airtightness to be examined at similar pressure differentials with minimal interference from climatic forces. In this technique a small varying pressure difference is created across the building envelope, which can be distinguished from naturally occurring pressures. Because of this distinction the air flow through the envelope, due to the applied pressure differential, can be evaluated.

In practice a piston is used to create a continuous sinusoidal change in the internal volume of the building being examined. This creates a time-varying pressure difference across the envelope. The airtightness of the building affects the amplitude and phase of the pressure change due to the sinusoidal volume change.

By measuring the amplitude of the pressure response inside the building and the phase relationship between this pressure and the velocity of the piston, the air flow through the envelope can be evaluated. A full theoretical analysis of AC Pressurization is presented by Modera and Sherman [1986]. However, the basic principle of AC Pressurization is that by exciting a building with a sinusoidal volume change and measuring the pressure response at that frequency, the effect of random pressure fluctuations is significantly reduced. The pressure is measured directly whereas the flow is determined by computing the fraction of the rate of volume change which is in phase with the pressure. Compression of the air in the zone is out of phase with the pressure and therefore does not appear in the volume derivative pressure product used to compute the air flow rate. A more detailed account of AC Pressurization is presented in Section 6.9.

3.2 MEASUREMENT OF BUILDING COMPONENT AIRTIGHTNESS

The leakage characteristics of individual external building components can be evaluated from site measurements. In its simplest form this consists of sealing a chamber over the interior face of the building component (see Figure 3.2.1), supplying air to or exhausting air from the chamber at a rate required to maintain a specified static pressure difference across the specimen, and measuring the resultant air flow through the specimen.

The test can be made more accurate if the pressure in the room containing the component is balanced to that in the collection chamber. This pressure balancing can be performed by using a secondary or auxiliary fan located in the room envelope. With reference to Figure 3.2.2, fan 'a' is used to depressurize the room to a given pressure differential and fan 'b' is adjusted to maintain a zero pressure difference between the collection chamber and the room. The leakage flow through the target area is then measured at Q. The increase in accuracy is due to the elimination of unwanted leakage between the collecting chamber and the rest of the room.

Site measurements of component leakage can also be made by using a pressure compensating flow rate meter (e.g. Phaff [1987]). This device operates on the zero pressure principle whereby the resistance of the measuring instrument is compensated by means of a integral fan. This type of equipment was originally developed for measuring the flow rate at the supply and exhaust grilles of mechanical ventilation systems. When correctly adjusted the presence of the device does not influence the air flow and the flow rate can be determined directly.

For this particular application a collection chamber is placed over the area where the cracks are situated and the flow meter is placed over an opening in the box. By compensating the pressure difference the air flow through the cracks is evaluated. The

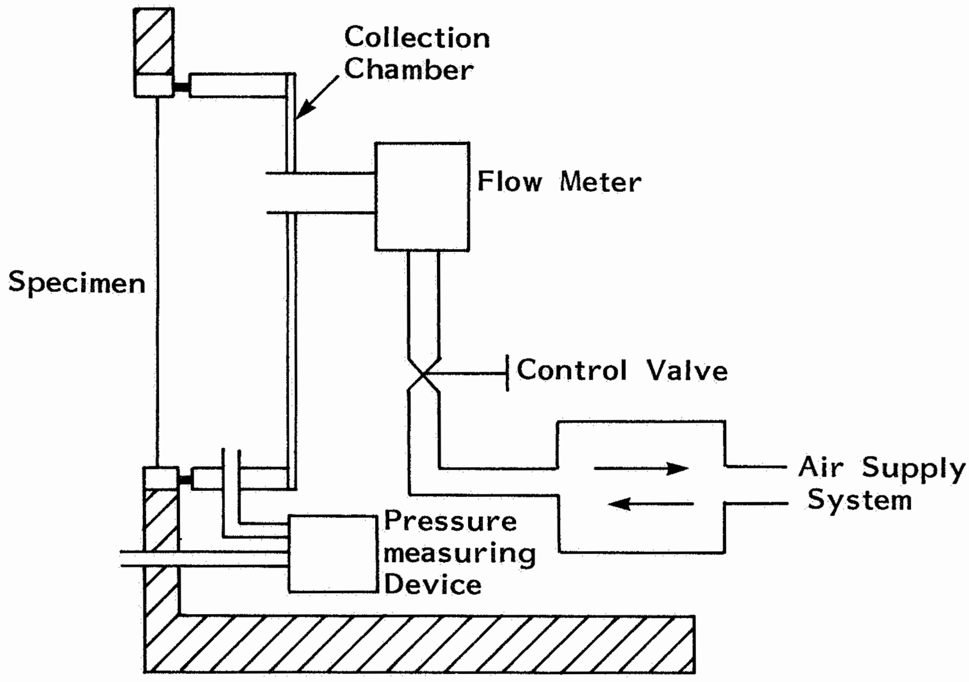


Figure 3.2.1 Schematic of component airtightness test using collection chamber (after ISO DP 9972 [1988])

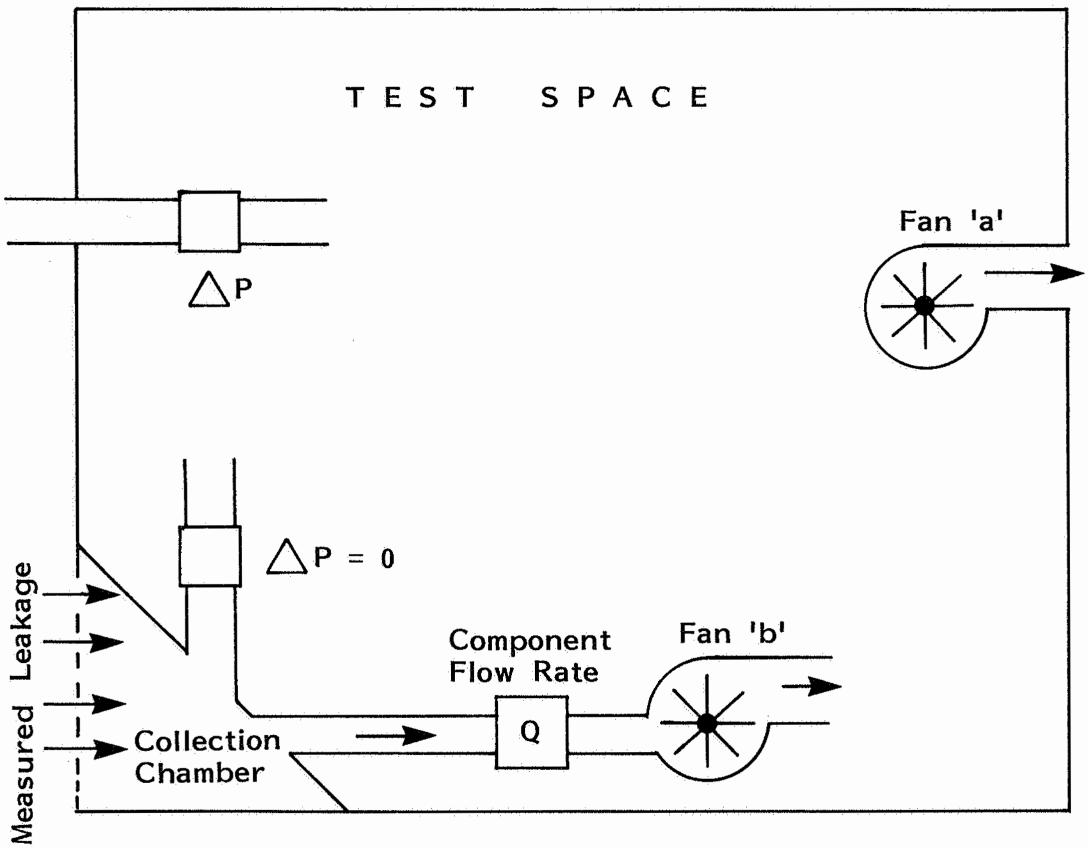


Figure 3.2.2 Use of secondary fan to increase accuracy of building component airtightness test (after BAKER and VALENTINE [1987])

collection chamber does not need to be airtight, as near pressure compensation unwanted leak flows will be minimal.

This type of device can also be used to asses leakage distribution during pressurization tests (see Figure 3.2.3). The building is pressurized in the normal way (see Section 3.1.1) and a shield of cardboard is placed in the opening of an internal door. The flow meter is placed over an opening in the shield and at pressure compensation the air flow through the room facade is indicated. Bypass flows through adjacent internal walls will be minimal near pressure compensation. However large internal leaks may make it impossible to see when compensation is reached.

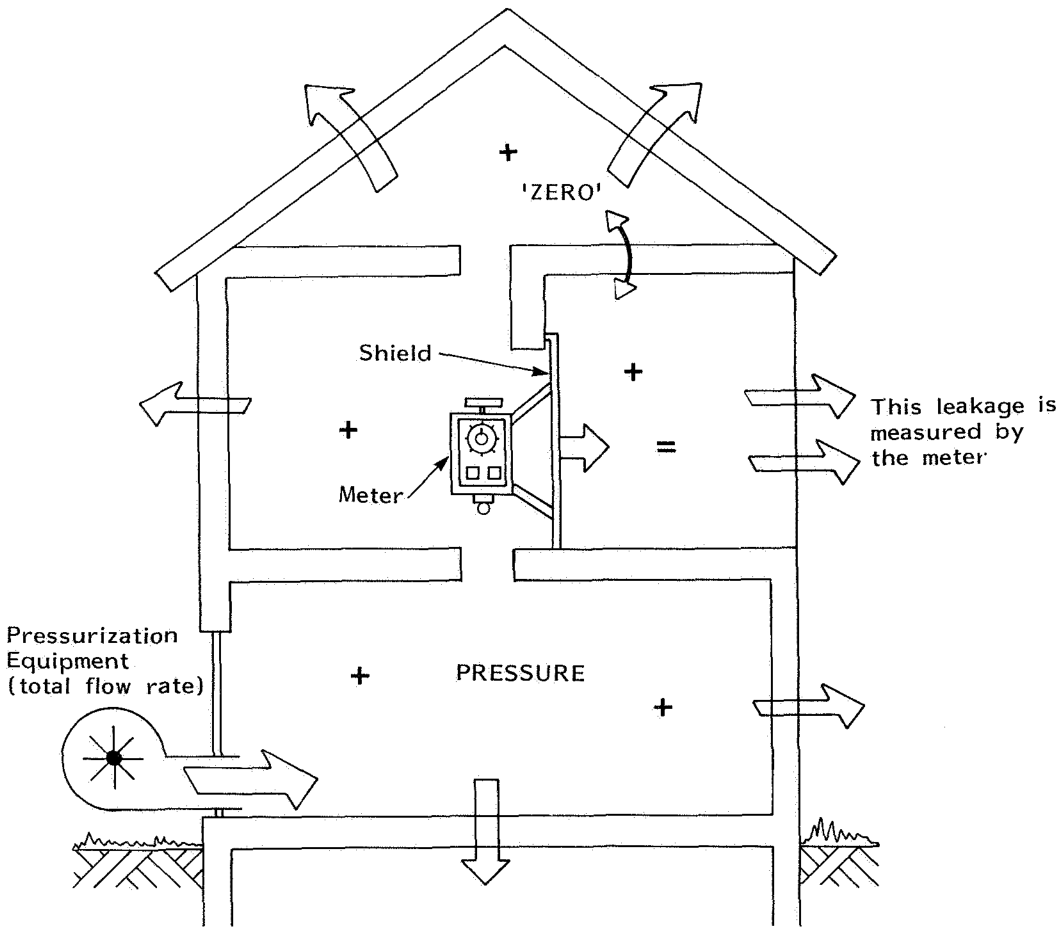


Figure 3.2.3 Pressure compensating flow meter being used during pressurization test (after PHAFF [1987])

Building component airtightness measurements can be performed under controlled laboratory conditions. A test chamber is used, into which various test specimens are fitted. The air flow through and the pressure difference across the test specimen can be accurately determined under laboratory conditions. This type of test has the advantage that large numbers of specimens can be examined under similar conditions, and the effect of climatic forces are nullified. The results of such tests are often reported in terms of leakage per unit area or leakage per unit crack length (see Section 3.3). It must be noted that laboratory based measurements may produce significantly different results to site evaluations of seemingly identical components. This is mainly due to the fact that laboratory workmanship may be under closer control than that on site.

The air leakage through the whole surface of individual external or internal walls can be evaluated using a technique known as balanced fan pressurization. This method is particularly appropriate for large multi-celled buildings such as apartment blocks or multi-family dwellings. For example consider one apartment in a multi apartment building. The apartment will have a single external wall with up to five other walls being shared with adjoining corridors or apartments. If a normal fan pressurization test such as that described in Section 3.1.1 is performed, the measured leakage will include the leakage to several internal zones.

If however the pressure in these other zones is balanced with that in the main test zone i.e. zero pressure difference across internal walls, then no air leakage will occur through internal flow paths and only the leakage to the external environment will be evaluated.

In order to achieve this pressure balance each surrounding zone must be pressurized along with the main measurement zone. Thus more than one set of fan pressurization equipment is required for this type of test. Also control procedures are needed in order to maintain zero pressure differences where required.

The technique is not limited to multi-compartment buildings but it may also be used in a variety of other situations. For example, in a row of terraced houses, one house is pressurized in the normal manner whilst the adjacent houses are balanced to the same pressure. This enables the leakage through the external walls of the dwelling to be separated from the leakage through the partition walls. A full account of the balanced fan pressurization technique is presented by Rearden et al [1987].

3.3 PRESENTATION OF AIRTIGHTNESS MEASUREMENT RESULTS

Several means of expressing airtightness measurement results have been developed. Some of the more common expressions are examined below.

Flow coefficient and flow exponent

This method of expressing the results of airtightness measurement is applicable both to the building envelope and individual building components. By making pressure difference and flow rate measurements the following generalized leakage function can be determined.

$$Q = k(\Delta P)^n \qquad (m^3 s^{-1}) \qquad [3.3.1]$$

Where:

Q = Air flow rate, $m^3 s^{-1}$

ΔP = Pressure differential, Pa

k = Flow coefficient, ($m^3 s^{-1}$ at 1 Pa)

n = Flow exponent

Values of k and n describe the air leakage characteristics of the tested envelope or component over the range of flows and pressure differentials examined. This power law function is illustrated in Figure 3.3.1.

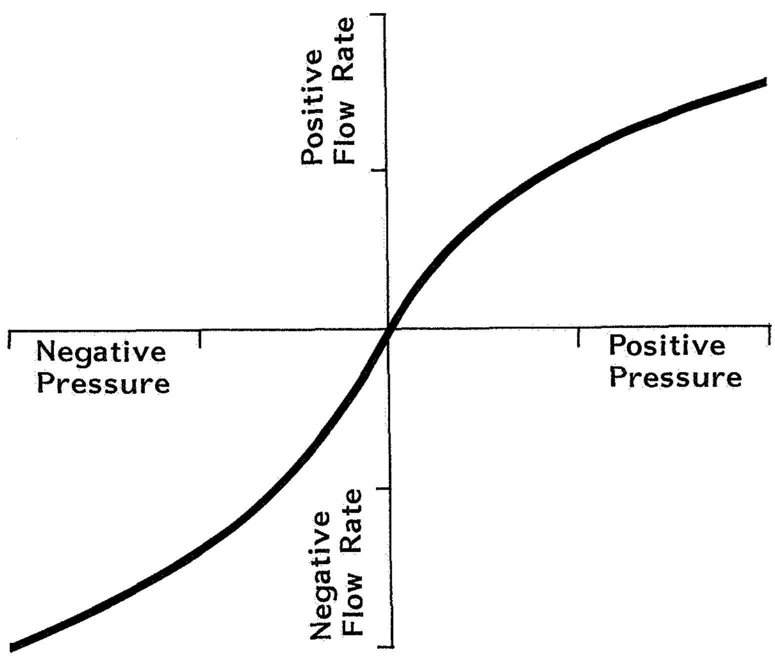


Figure 3.3.1 Air leakage characteristics (Power law plot)

Air change rate at 50 Pa

The air change rate at 50 Pa is a single number which in some cases may be adequate to describe the air leakage characteristics of the building envelope. Often referred to as the N_{50} value, it can be evaluated by substitution into Equation 3.1 or by direct measurement of air flow rate at 50 Pa. In several countries this value has been adopted as a standard when assessing buildings in terms of airtightness (see Section 5.2).

Equivalent leakage area

The building envelope has numerous cracks and penetrations which allow air to flow through them. The equivalent leakage area (ELA) is a measure of the total area of all the various cracks in the envelope. It is calculated as the area of a sharp edge orifice which would pass the same volume flow as the building at a given pressure difference. The ELA is dependent upon pressure difference and the pressure difference must be stated when presenting ELA values. One means of evaluating the ELA is given in Equation 3.2.

$$ELA = \frac{Q}{Cd\left[\frac{2\,\Delta P}{\rho}\right]^{1/2}} \qquad [3.3.2]$$

Where:

ELA = Equivalent leakage area, m^2

Q = Volume flow rate, m^3s^{-1}

Cd = Discharge coefficient, 0.6

ρ = Density of air, $kg\,m^{-3}$

ΔP = Pressure differential, Pa

Several airtightness measurement standards (see Section 5.2) require the results of the tests to be presented in terms of equivalent leakage area.

The ELA is representative of the total leakage area of a building. It is evaluated independently of building volume or envelope area. The specific leakage area (SLA) enables the equivalent leakage area of several buildings to be compared by normalizing the results in terms of the floor area of the building.

Hence:

$$SLA = \frac{ELA}{\text{Floor Area}}$$

Alternatively the equivalent leakage area can be expressed in terms of the envelope area. This is the normalized leakage area (NLA).

Where:

$$NLA = \frac{ELA}{\text{Envelope Area}}$$

Leakage rate per unit area or length

The leakage air flow rate, often in litres/s per unit length of crack or unit area of building envelope, is presented. Again the exact pressure difference at which the flow rate is evaluated must also be given.

3.4 LEAKAGE LOCATION AND QUALITATIVE TECHNIQUES

There are a number of measurement techniques which provide qualitative information about air infiltration and ventilation in related parameters. Several of these methods are designed to provide information about the sources of air leakage in buildings. The most sophisticated of these methods is infra-red thermography. In this technique thermal radiation, which depends on the surface temperature, is converted by the infra-red radiation sensing system (thermographic camera) to a visible thermal image. In order to detect leakage defects, the building is usually depressurized in some manner. The technique works best when there is a distinct temperature difference between the inside and outside of the building. The ingress of cold external air then cools the surfaces adjacent to the cracks. These cold areas are revealed on the thermal image and leaks can be located. It is also possible to detect air leakage from the living space to the roof space by pressurizing the building and observing the flow of warm air into the attic. A full account of the use of the application of thermography to air infiltration and airtightness measurements is given by Pettersson and Axen [1980].

Thermal imaging equipment is expensive and requires a high level of expertise to operate it effectively. The main difficulty lies in being able to separate air leakage paths from other thermal anomalies in the envelope e.g. thermal bridges. Smoke tests offer a cheaper and easier alternative for leak detection. Smoke can be produced in several ways, the most convenient often being a hand-held puffer and smoke stick (see Figure 3.4.1), and the technique simply involves pressurizing a building and using a smoke source to trace the paths followed by the leaking air. Smoke can also be used for flow visualisation through larger openings such as internal doors.

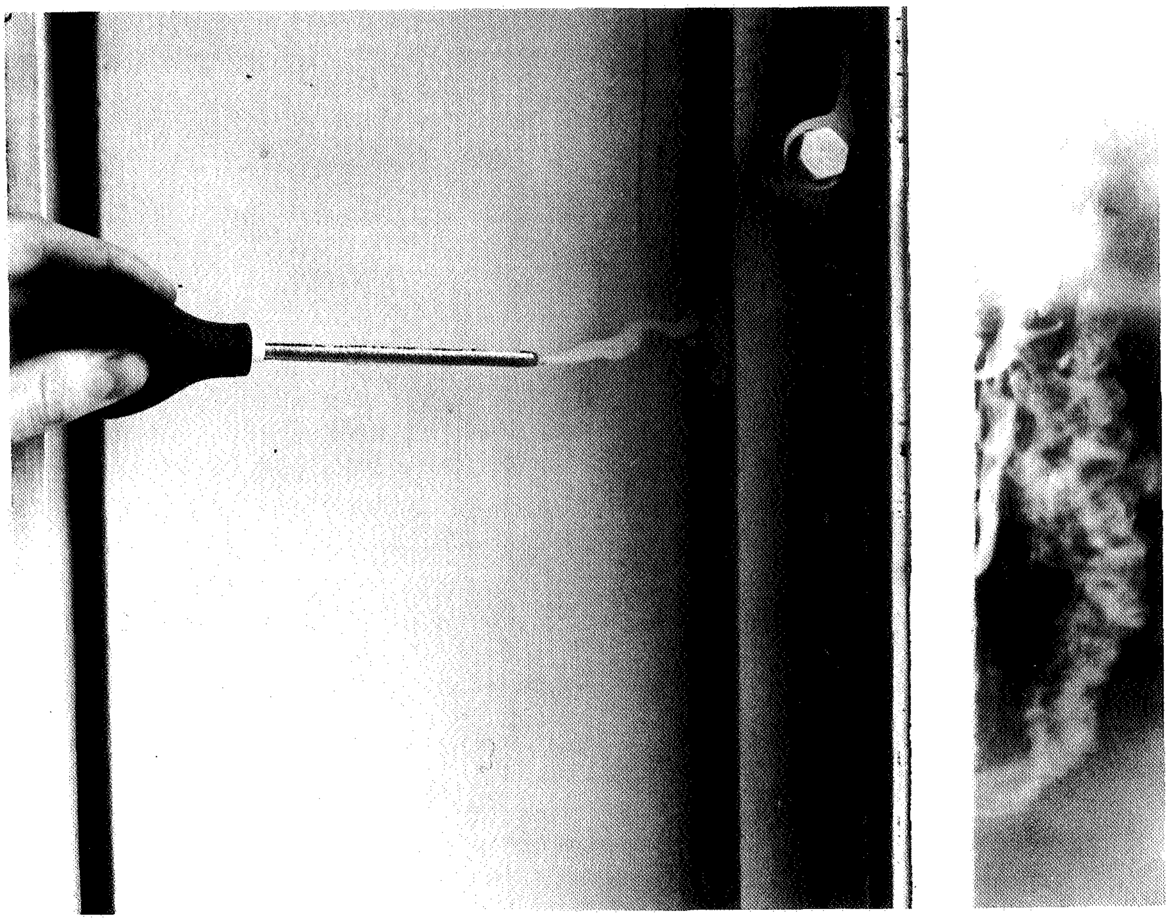


Figure 3.4.1 Smoke visualization method (after DICKSON [1981])

Sound waves pass readily through many of the same openings in the building envelope that allow air leakage. Acoustic detection of leakage paths is therefore possible. A steady, high-pitched sound source is placed within the building and leaks are "listened for" on the external surface. A small microphone or stethoscope is used and leaks correspond to an increase in the intensity of transmitted sound.

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CHAPTER 4: Equipment and Instrumentation

CHAPTER 4 EQUIPMENT AND INSTRUMENTATION

This chapter examines some of the specialist equipment and instrumentation required to perform air exchange and airtightness measurements.

4.1 TRACER GASES

Tracer gases are used for the evaluation of air change rates and interzonal air flows. Several authors have discussed the characteristics of an ideal tracer gas (e.g. Hunt [1980], Kronvall [1980]). For safety considerations the gas should be neither flammable nor explosive and, as measurements are often performed in occupied buildings, it should have no adverse health effects in the concentrations required for the tests. A further requirement of a gas used as a tracer is that its concentration must be measurable to a good order of accuracy, even when highly diluted. The tracer should be cheap and readily available. The gases present in ordinary air should not affect the tracer gas analysis. The tracer gas should not be normally present in outdoor air thus allowing the external concentration to be assumed to be zero. There should be no natural source of tracer within the enclosure, hence the source term in the tracer continuity equation (See Section 2.1) will consist solely of the tracer deliberately produced for the test. The tracer, which should have a similar density to air, must not be absorbed by walls or furnishings, or decompose, or react with building surfaces or constituents of air. This ensures that all the tracer leaving the enclosure does so by the process of ventilation.

No gas fulfils all the requirements given above, but historically several gases have been used as tracers, with various degrees of success. Hydrogen and helium were among the first gases used as tracers. Both are easy to detect with a katharometer. This device measures the thermal conductivity of the gas mixture and relates it to the tracer concentration. However, these gases have densities which differ considerably from those of air. Hydrogen is also flammable and, in certain concentrations with air, explosive. Methane and ethane have also been used as tracers. Both gases fulfil most of the requirements for a good tracer except that they are capable of forming explosive mixtures with air. Many other gases have been tried as tracers, these include chloroethane, carbon monoxide, ammonia, argon 41 and acetone. Several of these compounds fail to meet some of the requirements for a good tracer. A detailed account of the use of these and other gases as tracers is given by Hitchin and Wilson [1967]. Currently popular tracer gases include nitrous oxide, carbon dioxide, sulphur hexafluoride, freons and perfluorocarbons.

4.1.1 Comparison of Tracer Gases

Both Grimsrud et al [1980] and Shaw [1983] compared air exchange rates as measured with different tracers. Grimsrud et al concluded that air exchange rates measured using sulphur hexafluoride are slightly larger than those measured with nitrous oxide or methane. Shaw established specific air change rates in a test chamber with a fan and flow meter. He then compared this rate with air change rates measured with two or more tracers. The agreement between fan-induced and tracer measured flow rates was slightly worse for sulphur hexafluoride and carbon dioxide than for methane, carbon monoxide and nitrous oxide.

Table 4.1.1 presents some of the salient properties of several tracer gases. It must be noted that inclusion in Table 4.1.1 does not imply that a particular gas is ideally suited to all types of tracer gas measurement. Also other gases may be suitable for tracer measurements.

Two important parameters are considered in Table 4.1.1.

Maximum concentration

In terms of density the maximum concentration is set arbitrarily at the level of tracer concentration above which the air/tracer mixture would differ from air by 1%. From safety considerations the maximum allowable level is presented in parts per million. These levels (except for the value for nitrous oxide) are set by the following organisation:

Occupational Safety and Health Administration
Department of Labor
200 Constitution Avenue NW
Washington DC 20210
USA

The nitrogen dioxide limit is given by the American ASTM Standard E 741-83 for the tracer dilution (decay rate) measurement technique (See Section 5.1.4 for details of this standard).

It must be noted that the safety limit values presented in Table 4.1.1 may only apply to regions covered by the above governing bodies. National or local exposure limits must always be adhered to when using any tracer gas within an occupied building.

Minimum concentration

The minimum detectable concentration of each tracer, when using the two most common means of detection (see Section 4.2), is presented. This does not necessarily preclude the detection of these tracers by other means, nor indicate that future instrumentation developments will not lower these values.

Finally several remarks are presented which give a broad outline of the tracer gases' uses and limitations.

TABLE 4.1.1. PROPERTIES OF A SELECTION OF TRACER GASES

TRACER	FORMULA	DENSITY Compared to air at NTP	MAX CONCENTRATION		MIN CONCENTRATION		COMMENTS
			For Density % by volume	For Safety ppm	Infra-red ppm	Electron capture	
Nitrous oxide	N_2O	1.53	1.89%	25	0.20	–	Anaesthetic gas. Can form explosive mixtures in air. Widely used as a tracer
Carbon dioxide	CO_2	1.53	1.89%	5000	0.40	–	High background concentration due to occupants. Readily available
Sulphur hexafluoride	SF_6	5.10	0.24%	1000	0.01	1pp 10^{13} air	Decomposes at 550°C. Detection effected by other halogenated compounds in air. Widely used as a tracer
Freon F-12	CF_2Cl_2	4.17	0.32%	1000	0.06	60pp 10^9 air	Detection effected by other halogenated compounds in air. Used in multi-tracer work
Freon F-114	$CClF_2CClF_2$	5.90	0.20%	1000	0.06	135pp 10^9 air	Detection effected by other halogenated compounds in air. Used in multi-tracer work
Freon BCF	$CBrClF_2$	3.34	0.43%	–	–	0.5pp 10^9 air	Detection effected by other halogenated compounds in air. Used in multi-tracer work
Perfluorocarbon PMCH or PP2	$CF_3C_6F_{11}$	Liquid at NTP	–	–	–	1pp 10^{12} air	Released by vaporisation or diffusion. Used in passive sampling methods
Perfluorocarbon PDCH or PP3	$CF_3CF_3C_6F_{10}$	Liquid at NTP	–	–	–	1pp 10^{12} air	Released by vaporisation or diffusion. Used in passive sampling methods

4.2 TRACER GAS ANALYSERS

The role of the gas analyser is to determine, as accurately as possible, the concentration of tracer gas in a sample of air from the measured space. For some techniques the gas analyser must be transported to and used at the measurement site. In these cases the analyser should be both robust and portable. Several measurement techniques exist where the air/tracer samples are obtained at the measurement site and returned to the laboratory for concentration analysis. Here the gas analyser may be less portable and, in some cases, more sophisticated than its on site counterpart.

4.2.1 Tracer Gas Analysis Methods

In terms of the basic principle of operation there are several types of gas analyser. Within each principle of operation group numerous commercial options exist. For these reasons only two common measurement principles are examined here.

Infra-red gas analysis

The concentration of nitrous oxide and carbon dioxide is usually evaluated using an infra-red absorption analyser. This method can also be used for sulphur hexafluoride concentration determinations. Infra-red analysis makes use of the fact that many gases exhibit energy absorption characteristics in the infra-red portion of the electromagnetic spectrum.

The amount of infra-red energy absorbed varies from gas to gas and is dependent on the concentration of absorbing gas in a sample. Elemental gases which are composed of multiple similar atoms, such as oxygen and nitrogen (which are the main constituents of air), do not absorb in the infra-red and, therefore, do not interfere with the detection of the tracer. One method of performing this analysis is to pass two beams of infra-red radiation of equal intensity through an analysis cell and parallel reference cell respectively. The analysis cell contains a sample of air in which the tracer gas is present, while the reference cell contains a non-absorbing reference gas. The difference in intensity between these two streams after passing through the cells is monitored, and this provides a measure of the tracer gas concentration. A second practical method is available which removes the necessity for a reference cell. Two narrow bands of infra-red energy are generated, one at a reference and one at a measurement wave length. These are passed alternatively through a sample in a sample cell. The remaining energy is collected and the ratio of the two energy levels is proportionate to the concentration of tracer gas.

Electron capture gas analysis

Some gases capture electrons; this property can be utilized to detect the concentration of tracers such as sulphur hexafluoride, perfluorocarbons and freons. Electron capture detectors use a small radioactive source to generate a cloud of electrons in an ionisation chamber. When a pulsed voltage is applied across the chamber, a current flows. A sample of gas is injected into the cell. If the sample contains a tracer which is electron capturing, then the number of electrons in the chamber is reduced. This in turn causes the current across the chamber to decrease. The reduction in current is proportionate to the tracer gas concentration. Atmospheric oxygen has electron capturing properties, so this type of detector is invariably used with a gas chromatograph upstream of the detector to separate the oxygen from the tracer gas. A gas chromatograph consists of a column containing a packed powdered solid. When an air sample is carried through the column each gas is absorbed and desorbed at different rates by the medium. This causes the component gases e.g. tracer gases and oxygen to arrive at the far end of the column at different times. Hence the gases can be individually analysed by the electron capture detector.

4.2.2 Choosing a Tracer Gas Analyser

Whatever measurement principle is used, several points must be considered when choosing a gas analyser for tracer gas studies. Ultimately the final choice may be based on financial considerations; however three technical factors are highlighted below.

Range of concentration determination

For several reasons (See Section 4.1) a tracer gas must be measured at very low concentrations. Therefore any gas analyser used in tracer gas work must be suited to this task. Some techniques require the tracer concentration to be measured over a range of values. The analyser must be able to cope with the range requirements of the specific technique for which it is to be used. This problem may be exacerbated in multi-tracer studies (See Section 2.2), where ideally, a single gas analyser will have to be able to evaluate the concentration of several tracer gases.

Accuracy of concentration determination

The accuracy of several tracer gas measurement techniques is dependent upon the accuracy at which the tracer gas concentration is determined. It is therefore of vital importance that the gas analyser be highly accurate, or if inaccuracies exist, that they are known or can be determined. Frequent calibration may be required in order to obtain a known accuracy. Despite their potential disruption to actual measurements, analyser calibration procedures must be recognised as an integral part of all tracer gas measurement techniques.

Sample analysis time

Some tracer measurement techniques require the gas concentration to be determined continuously or at short discrete intervals. The amount of time required to determine the tracer gas concentration in an air sample and prepare the analyser to receive the next sample is of importance when choosing a gas analyser for any particular tracer technique.

4.3 COMMERCIAL DC PRESSURIZATION EQUIPMENT

Measurements of building envelope airtightness can be performed by using a fan which is temporarily installed in the building envelope. This type of equipment was initially developed as a research tool. Versions of this type of equipment are now available from several commercial organisations. This equipment is often known as a Blower Door. Most manufacturers of such equipment are located in the USA but some are based in Europe (see Table 4.3.1). Most doors are designed to cope with domestic situations although at least one manufacturer produces a multi-fan door which finds application in light industrial buildings and commercial premises.

TABLE 4.3.1. SEVERAL BLOWER DOOR MANUFACTURERS

Air Quality Labs, Inc. CARE, Cap Door Vista Industrial Park Building 5 Spokane, WA 99206 USA Tel: (509) 325-4281	Infiltec Infiltec R-1, E-1, E-2 5597 Seminary Road Suite 2412 South, PO Box 1533 Falls Church, VA 22041 USA Tel: (703) 820-7696
Eder Energy Detecdoor SA-1, CA-2, CA-3 7535 Halstead Dr. Mound, MN 55364 USA Tel: (612) 446-1559	Mekankonsult Lifa Gökvägen 13 S-35242 Växjö Sweden Tel: (470) 22956
The Energy Conservatory Minneapolis Blower Door 920 West 53rd Street Minneapolis, MN 55419 USA Tel: (612) 827-1117	Retrotec Retrotec Door Fan PO Box 5632, Station F Ottawa, ONT Canada K2C - 3M1 Tel: (613) 723-2453
Your Energy Service Y.E.S. Door 2204 Elliston, Suite F Nashville, TN 37203 USA Tel: (615) 329-9747	Elmicro Box 22 S-360 50 Lessebo Sweden Tel: (478) 11376

NB: The Air Infiltration and Ventilation Centre does not necessarily endorse the equipment supplied by these manufacturers.

4.3.1 <u>Blower Door Design</u>

Blower door design varies from manufacturer to manufacturer but essentially each door comprises a variable flow rate fan and some means of holding the fan in place in an existing door frame.

Two door frame systems are in general use. In the first, rigid modular panels are used to fill the door frame. These panels are fitted with sliding extension pieces which can be locked in place once the panel has been expanded to the size of the door frame. One panel contains the fan and the modular approach is used to ease transportation of the equipment from one site to another. A modular panel blower door is shown in Figure 4.3.1.

Figure 4.3.1 Blower door. Modular panel type. Retrotec (see Table 4.3.1)

A second method uses a metal frame which can be expanded to match the dimensions of the door frame. This is then covered with a strong nylon or polythene fabric thus providing the required seal. The fan then rests on the floor and penetrates the fabric through a tightly fitting opening. This type of door is illustrated in Figure 4.3.2.

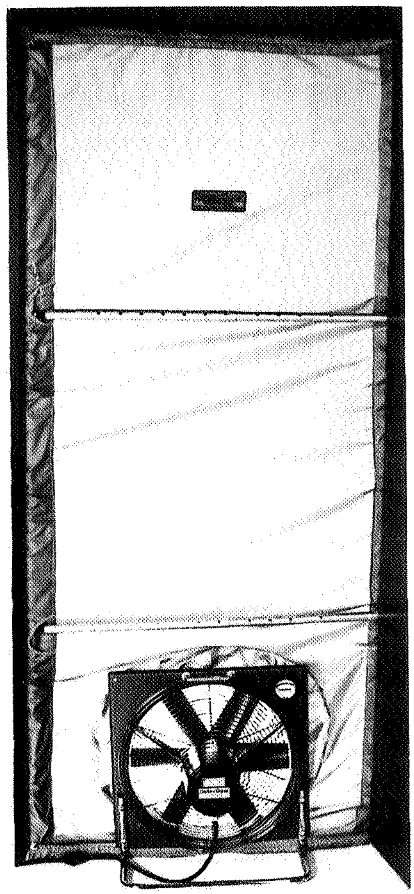

Figure 4.3.2 Blower door. Expanding frame type. Eder Energy (see Table 4.3.1)

The major working component of the blower door is the fan. This must be powerful enough to create the range of volumetric flow rates required for the test. The flow rate required will depend upon the volume of the building and its airtightness at the pressure differentials reached. In order to facilitate pressurization and evacuation measurements, the flow should ideally be reversible. This can be achieved physically, i.e. turning the fan around, or electrically, i.e. reversing the rotation of the blades. Some door fans are powered by direct drive DC motors and others by variable speed AC motors.

Several door fans are produced which are uncalibrated in terms of air flow rate. These instruments may only be used for the qualitative location and assessment of air leakage sites. However, most doors are calibrated thus enabling the air flow through the fan to be evaluated. Direct flow measurement techniques are based on the relationship between the air flow rate through a nozzle or orifice and the pressure drop across such a constriction. This is a well understood technique (see, for example Ower and Pankhurst [1977]), and in practice would involve, for example, measuring the static pressure drop across the fan inlet. The flow rate is then evaluated from this pressure drop using an equation derived from calibration data. The restriction required to produce the pressure drop may decrease the flow capacity of the fan.

A second technique employed involves calibrating the flow rate in terms of the fan speed and the internal/external pressure difference (see, for example, Persily [1984]). The air flow rate is given by the general function

$$Q_F = f(\omega, \Delta P) \qquad [4.3.1]$$

Where

Q_F = Airflow rate through fan, m^3s^{-1}

ω = Fanspeed, s^{-1}

ΔP = Pressure differential, Pa

The relationship between the above parameters can be derived by using the blower door to pressurize a calibration chamber. The air flow rate out of the chamber is measured together with the fan speed and the chamber pressure differential. A family of curves is derived (see Figure 4.3.3) and the air flow rate is obtained on site from measurements of fan speed, using a tachometer, and inside/outside pressure difference. Hence the output from a blower door will minimally consist of pressure and/or fan speed readings.

Several companies can also supply a variety of computer hardware and software. This allows the tests to be performed with greater ease and accuracy and enables estimates of parameters such as air change rate or effective leakage area to be obtained directly. These packages range from the manual analysis of the raw data

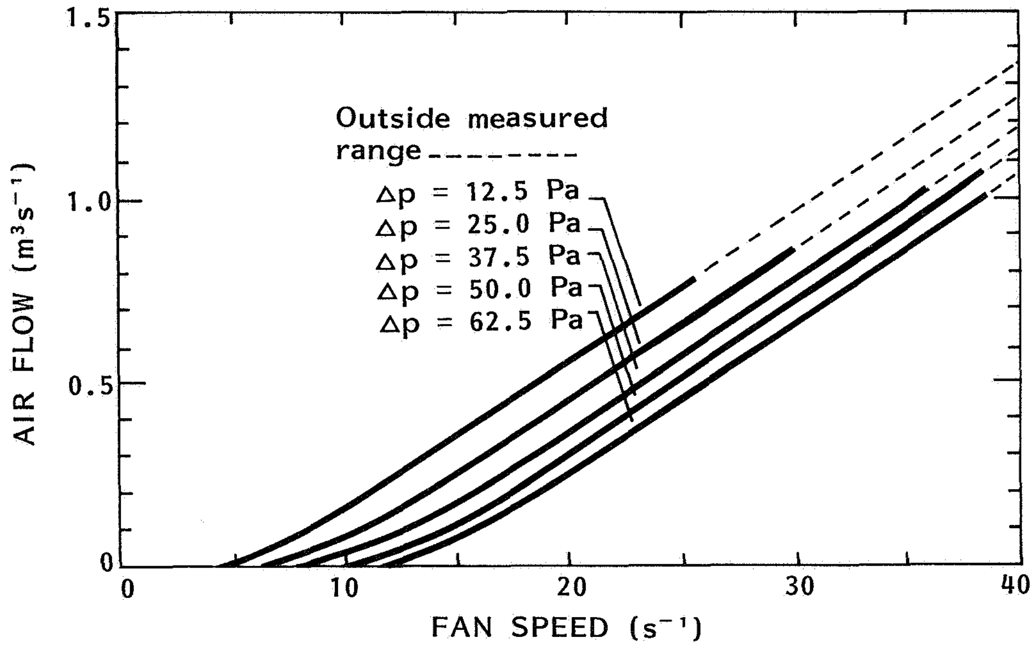

Figure 4.3.3 Example calibration curves for blower door equipment. See equation 4.3.1 (after PERSILY [1984])

with a hand-held computer or calculator, through automatic analysis by computers which are hooked up directly to the blower door, to sophisticated systems which will automatically run a series of tests at incremental pressure differences then provide digital read-outs, printed graphs and diagnostic data. In general, the more sophisticated the equipment the more expensive it will be and the analysis package often represents a significant proportion of the total cost of the blower door system.

4.3.2 Comparison of Several Blower Doors

As indicated in Section 4.3.1 commercial blower doors vary in design, sophistication and cost. Actual costs of blower doors will alter both with time and currency exchange rates so no indication of cost is given here. For current price information, individual manufacturers should be contacted - see Table 4.3.1.

Table 4.3.2 presents the relevant characteristics of several commercially available blower doors. The parameters examined are:

TABLE 4.3.2. SPECIFICATIONS OF A SELECTION OF BLOWER DOORS

MANUFACTURER AND MODEL	FLOW RATE TYPE P/T	OPENING SIZE, m		WEIGHT, kg		FLOW RATE RANGE m^3s^{-1}	QUOTED ACCURACY	FAN MOTOR TYPE AC/DC
		min	max	all	fan			
Air Quality Labs - CARE door	T	0.74 x 1.98	0.94 x 2.18	39	18	0.00 - 3.49	5%	DC
Air Quality Labs - CAP door	T	0.74 x 1.98	0.94 x 2.18	23	18	0.00 - 3.49	5%	DC
Eder Energy SA-1	NA	0.61 x 1.83	0.94 x 2.23	15	11	0.00 - 1.23	Non Calib.	AC
Eder Energy CA-2	P	0.61 x 1.83	0.94 x 2.13	19	15	0.00 - 1.65	5%	AC
Eder Energy CA-3	P	0.61 x 1.83	0.94 x 2.13	20	16	0.00 - 2.12	5%	AC
Energy Conservatory Minneapolis door	P	0.61 x 1.22	1.02 x 2.39	23	15	0.02 - 2.83	5%	AC
Infiltec R-1	P	0.71 x 1.98	0.91 x 2.23	34	18	0.25 - 2.24	5%	AC
Infiltec E-1	NA	0.71 x 1.98	0.91 x 2.23	36	18	0.00 - 1.60	Non Calib.	AC
Infiltec E-2	NA	0.71 x 1.98	0.91 x 2.23	38	18	0.23 - 1.60	Semi Calib.	AC
Mekankonsult Lifa blower door	P	–	0.88 - 2.08	18	8	0.02 - 0.84	5%	AC
Retrotec 710	P	0.76 x 1.92	0.96 x 2.19	48	17	0.01 - 2.78	5%	AC
Retrotec 720	P	0.76 x 1.92	0.96 x 2.19	49	17	0.01 - 2.26	5%	AC
Retrotec 650	P	See manuf.	See manuf.	69	53	0.00 - 6.37	5%	AC
Your Energy Service blower door	P	0.76 x 1.93	1.22 x 2.13	41	32	0.00 - 4.01	Non Calib.	AC

<u>Flow rate type</u>

This indicates the method by which the flow rate through the fan is measured.

P = Pressure Device
T = Tachometer (Fan Speed)
NA = Not applicable

An explanation of the above two methods is given earlier in Section 4.3.1.

Opening size

This gives the maximum and minimum opening size into which the door panel can be fitted. Some door frames may be too large for the panel to fill, but this may be overcome with an improvised seal. However, if the panel is too large for a given door frame then this may be a more difficult problem to resolve.

Weight

The weight of all the equipment and the fan alone is given. This can be an important factor if the blower door equipment has to be frequently transported from one measurement site to another.

Flow rate range

This is the flow rate range of the fan, usually when operating against a back pressure of 50 Pa. It is essential for the fan to be able to meet the flow rate requirements of the test. In general the larger and more leaky the building under test the greater the required flow rate capacity.

Quoted accuracy

This is the manufacturer's quoted accuracy for the rate of air flow through the fan. Often, especially if the blower door is to be used for research purposes, individual operatives will recalibrate the blower door during the course of its working life.

Fan motor type

This indicates whether the fan operates on Direct or Alternating Current.

The information presented in Tables 4.3.2 was gathered from individual manufacturers or adapted, with permission, from an article which originally appeared in "Energy Auditor and Retrofitter". "Energy Auditor and Retrofitter" is a magazine dealing with home energy conservation and is produced in Berkeley California (Tel:(415) 524-5405.)

4.4 INSTRUMENTATION FOR MEASURING CLIMATIC PARAMETERS

Many meteorological parameters can be measured or evaluated. However only the three parameters of most interest in infiltration and ventilation studies will be discussed here.

4.4.1 Wind Speed Measurement

The main climatic parameter of importance in infiltration and ventilation studies is the speed of the prevailing wind. Air change rates and interzonal air flows are dependant upon wind speed, and the accuracy of pressurization tests is affected by this parameter. Depending upon the nature of the measurement being performed, wind speed measurements can be either made on site or obtained from a nearby meteorological station.

Simple site measurements can be made by observing the physical effects of the wind in the area surrounding the test building (for example tree, smoke or water movement), and estimating wind speed from standard charts.

A complete record of the wind speed during a measurement can be obtained by using a cup anemometer coupled to a chart recorder or data logger. In the case of some sophisticated measurement techniques the anemometer may be directly connected to and recorded by the equipment used to perform the air infiltration and ventilation measurements.

Due to the frictional influence of the earth's surface, the mean wind velocity varies with height above the ground. The wind speed at any location is influenced by the nature of the surrounding terrain, and the degree of local shielding by buildings and other obstacles. Therefore in all cases where the wind speed is measured on site, by whatever method, the exact location and height of the measurement point must be recorded. Ideally some information about the surrounding terrain should also be provided.

It is not always possible or desirable to evaluate the wind speed at the measurement site. This is especially true when simultaneously examining large numbers of buildings in the same general area. In this case it is advantageous to obtain more generally applicable meteorological data from, for example, a weather station.

The number and distribution of sources of meteorological data vary from country to country and for further information the relevant Meteorological Institute should be contacted.

4.4.2 Wind Direction Measurement

Wind direction also plays a role in determining air exchange rates within buildings. Although probably not as important as wind speed, wind direction does exert an influence especially where leakage paths are not evenly distributed over the building envelope. Site estimates of wind direction may be made by direct observation and can be presented in terms of the direction of the wind with respect to the building. By using a compass absolute wind direction values may be estimated. Continuous measurements can be obtained by using a wind vane and data logging device. Alternatively, like wind speed, general wind direction data can be obtained from weather stations or meteorological offices.

4.4.3 Air Temperature Measurement

Another important driving force of air infiltration and natural ventilation is internal/external temperature difference. This produces a density difference between the indoor and outdoor air and thus promotes air flow through the envelope by buoyancy effects. During pressurization tests the outdoor air temperature must be noted in order to calibrate the air flow rate measurement device.

Outdoor air temperature measurements may be made with a simple mercury glass thermometer or a thermocouple connected to a data logger or chart recorder. In all cases the thermometer must be protected against solar radiation which would otherwise raise the recorded temperature above that of the actual prevailing air temperature. Air temperature data may also be obtained from weather stations and meteorological offices. Internal air temperature measurements must also be made in order to evaluate the temperature difference across the building envelope.

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CHAPTER 5: Measurement Technique Standards

CHAPTER 5 MEASUREMENT TECHNIQUE STANDARDS

Several measurement techniques have become subject to standardisation. This chapter examines a selection of standards and regulatory documents which relate to air exchange rate and airtightness measurement techniques.

5.1 AIR CHANGE RATE MEASUREMENT TECHNIQUE STANDARDS

The air change rate of a building is usually evaluated using tracer gas methods (See Section 2.1). Several countries have developed standards relating to this type of measurement. Table 5.1.1. presents several of these standards giving for each its country of origin, governing body, designation, title, type of measurement to which it refers, and level of accuracy expected.

TABLE 5.1.1. AIR CHANGE RATE MEASUREMENT STANDARDS

Country	Governing Body	Contact Address	Designation	Title	Measurement Principle	Accuracy
Nordic*	NORD-TEST	Post Box 111 SF 02101 Espoo Finland	NT VVS 048	Buildings: Total flow rate of air – continuous measurement	Constant concentration	5–10%
Nordic*	NORD-TEST	As above	NT BUILD 232	Buildings: Rate of ventilation in different parts of a building	Decay rate site analysis	10–20%
Sweden	BST	Building Standards Institute Drottning Kristinas Väg 73 S-114 28 Stockholm, Sweden	SS 02 15 56	Buildings: Determination of outdoor air inflow	Decay rate site analysis	12–18%
USA	ASTM	1916 Race St Philadelphia Pa 19103 USA	E741-83	Determining air leakage rate by tracer dilution	Decay rate site analysis and grab sampling	10%

*Nordic countries are: Denmark, Finland, Iceland, Norway and Sweden

Summaries of the standards referred to in Table 5.1.1 are presented below.

5.1.1 Nordic Standard NORDTEST NT VVS 048

This document describes a standard technique for the continuous measurement of air change rate in occupied and unoccupied buildings using the constant concentration tracer gas technique. Section 2.1.3 presents further details of the theory and practice of this method. The technique can be used for continuous determination of the infiltration of outside air into an entire building or individual rooms of a building. Air change rates are determined by measuring the amount of tracer gas required to maintain a constant concentration of tracer gas in the measured enclosure. Fully automated equipment is required to make this type of measurement. Section 6.5 contains a detailed description of a constant concentration measuring device. Besides explaining the principles of the measurement technique this document describes the equipment required for the test, the preparation of the building under examination and the measurement procedure. The expression of the results and the accuracy of the technique are also discussed. A standard reporting format for the test is also included.

5.1.2 Nordic Standard NORDTEST NT BUILD 232

This document describes a standard technique for monitoring the natural and forced ventilation rate in different parts of a building. The method can be used in all types of building. Practical difficulties can limit its range of application. Problems occur mainly in buildings with large volumes and high ventilation rates. Difficulties in interpreting the results can arise when examining buildings with large interzonal air flows.

The ventilation rate is evaluated using the tracer dilution (decay rate) method. A suitable tracer gas is distributed within the volume to be evaluated, and air samples are taken for analysis from locations where the air change rate requires measuring. The decay of the tracer gas is directly correlated with the ventilation rate in various parts of the buildings. Section 2.1.1 presents details of the theory and practice of decay rate measurements.

The principle of the measurement is explained, equipment suitable for making the test is described and the measurement procedure is presented. Other sections in the document examine the preparation of the test building, the expression of the results, and the accuracy of the technique. A standard format for the test report is presented.

5.1.3 Swedish Standard SS 02 15 56

This standard applies to the determination of outdoor air flow into buildings. The outdoor air flow can be created by mechanical or natural ventilation and the standard is primarily applicable to single family houses, flats and cell offices. It can be used to determine the total outdoor air flow into a single family house or flat or, the total outdoor air flow into an individual room which has both intake and extract mechanical ventilation.

The method is based on the dilution of tracer gas (decay rate) and the continuous measurement of the tracer gas within the building. Two methods are described: in the first the tracer gas concentration is measured in every room of the house or flat; in the second the tracer gas concentration is measured in only one room in the house or flat. The first method produces the best measurement accuracy but the second requires less equipment.

The standard describes the mathematical basis of the test and lists the equipment required to perform the measurements. The preparation of the building is described and the measurement procedure presented. Data collection and analysis is considered as is the accuracy of the method. Finally a standard reporting format for the test is presented.

5.1.4 USA Standard ASTM E 741-83

This standard describes a technique for measuring the air change rate of buildings under natural meteorological conditions using the tracer gas dilution (decay rate) principle. Two variants of the technique are presented. In the "on site monitor" variant, tracer concentration as a function of time is measured on site directly as air samples are obtained. Further details of this type of technique can be found in Section 6.1. In the "container sample" variant, after the tracer has thoroughly mixed an initial air sample container is filled. The tracer is allowed to decay for a period of several hours during which a second and perhaps third sample container is filled. The samples can then be analysed at a remote laboratory and air change rates can be determined from the decay in concentration. Further details of this technique can be found in Section 6.2.

The document describes terms specific to the standard, explains the principle of the measurements and explains the significance and use of the technique. Apparatus particular to the method is described and the measurement procedure presented. The initial data analysis and the presentation of the final results are examined. Calibration and safety procedures are considered and a standard reporting format for the test is presented. A list of suitable tracer gases is included.

5.2 AIRTIGHTNESS MEASUREMENT TECHNIQUE STANDARDS

The airtightness of buildings and building components can be evaluated using fan pressurization methods.

Several countries have developed standards relating to site measurements of building airtightness. Table 5.2.1 presents several of these standards, giving for each its country of origin, governing body, designation, title and type of measurement to which it refers. Summaries of the standards referred to in Table 5.2.1 are presented below.

5.2.1 Canadian Standard CAN/CGSB - 149.10 - M86

This standard relates to a method for the determination of the airtightness of building envelopes. The method is applicable to

TABLE 5.2.1. AIRTIGHTNESS MEASUREMENT STANDARDS

Country	Governing Body	Contact Address	Designation	Title	Measurement Principle
Canada	CGSB	The Secretary, Canadian General Standards Board Ottawa K1A 1G6 Canada	CAN/ CGSB 149.10 M86	Determination of the airtightness of building envelopes by the fan depressurization method	Fan depressurization
Netherlands	Nederlands Normalisatie-instituut	Kalfjeslaan 2, Postbus 5059 2600 G8 Delft Netherlands	NEN 2686	Air leakage of buildings – method of measurement	Fan pressurization or Fan depressurization
Nordic*	NORD-TEST	Post Box 111 SF-02101 Espoo Finland	NT BUILD 220	Buildings: Local air tightness	Fan pressurization or Fan depressurization
Sweden	BST	Building Standards Institute, Drottning Kristinas Väg 73 S-114 28 Stockholm, Sweden	SS 02 15 51	Buildings: determination of airtightness	Fan pressurization and Fan depressurization
USA	ASTM	1916 Race St Philadelphia Pa 19103 USA	E779-87	Determining air leakage rate by fan pressurization	Fan pressurization or Fan depressurization
USA	ASTM	1916 Race St Philadelphia Pa 19103 USA	E783-84	Field measurement of air leakage through installed exterior windows and doors	Fan pressurization or Fan depressurization
International	ISO	1, rue de Varembé Case postale 56 CH-1211 Genève 20 Switzerland	Draft Proposal DP-9972	Measurement of Building Air Tightness using Fan Pressurization	Fan Pressurization or Fan Depressurization

*Nordic countries are Denmark, Finland, Iceland, Norway and Sweden

small detached buildings (especially houses), but with appropriate modifications, it can be used for other buildings or parts of buildings. A fan or fans are used to exhaust air from the building at rates required to maintain the specified pressure differences across the building envelope. With the complete envelope subjected to simultaneous and similarly directed air pressure, air flows and pressure differences are measured. Air flow is corrected to reference temperature and pressure and the relationship between the flow and the pressure difference is used to evaluate the equivalent leakage area of the building envelope (see Section 3.3).

The standard describes the apparatus required to perform the tests and the laboratory calibration of this apparatus. Preparation of the building and the setting up of the test equipment is given attention. A detailed description of the test procedure is given, and the process of evaluating the equivalent leakage area from the test data is presented in full. A standard format for the test report is given.

5.2.2. Netherlands Standard Nederlandse Norm NEN 2686

This standard is presently available only in the original language. The standard describes a technique for the pressurization or depressurization of building components or the building envelope. Although the standard applies to all types of buildings, special emphasis is placed on the measurement of dwellings.

To ensure accuracy a minimum of at least 6 pressure differences and corresponding flow rates must be measured. Pressure differences must be in the range of 15-100 Pa. The results can be shown graphically. The final result is a flow rate through the envelope at 10 Pa. For convenience an equivalent leakage area can be calculated using the equation presented in the standard. The results must be presented in accordance with the given standard reporting format.

5.2.3. Nordic Standard NORDTEST NT BUILD 220

This NORDTEST document describes a method for evaluating the air leakage characteristics of individual building components or joints between components under field conditions.

The object to be measured can be in any building or structure which can be exposed to a pressure difference. However, the surface of the object must be directly accessible and easy to border on the side where the measurement apparatus is to be placed. Thus a covering structure, such as a lowered ceiling, which encloses an open air space against the object may prevent the measurement.

The test object will form part of the boundary of an enclosed room or building. A collection chamber is placed over the measured object. The chamber is equipped with a fan and a volume flow meter for evaluating the air flow rate through the test piece. A pressure measurement device is utilized to measure the pressure differential across the test component. A second fan is used to pressurize the room or building containing the test piece. This is used to balance the pressure between the room and the collection chamber, thus eliminating any unwanted leakage from the chamber. This compensating pressure can be provided by an auxiliary fan or the building's ventilation system. Once the required pressures have been balanced then the component flow rate and pressure difference measurements can be made. Further details of this type of technique are presented in Section 3.2.

This document describes the equipment required to perform the leakage test, the preparation of the building component or joint, the test procedure and the presentation and accuracy of the results.

5.2.4 Swedish Standard SS 02 15 51

This method applies to the determination of the rate of air leakage through the external envelope of a building resulting from a specified pressure difference. The method is designed to measure the total air leakage through the building elements or envelope surrounding a specific volume (a building or part of a building). A fan is used to supply air to or exhaust air from the building at rates required to maintain the specified pressure differences across the building envelope.

This Swedish standard is similar to the Canadian standard described in Section 5.2.1 except that this standard requires that both pressurization and depressurization tests be performed on the building. Also the results of this test are presented not in terms of the Equivalent Leakage Area but as the average air changes per hour at a pressure difference of 50 Pa across the building envelope.

The standard describes the apparatus required to perform the test, the preparation of the test building, the test procedure and the presentation of the results. The accuracy of the test is discussed and a standard reporting format for the test is presented.

5.2.5 USA Standard ASTM E 779-87

This test method describes a standardised technique for measuring air leakage rates through a building envelope under controlled pressurization or depressurization. The test method consists of mechanical pressurization or depressurization of a building and measurements of the resulting air flow rates at given indoor-outdoor static pressure differences. From the relationship between the air flow rates and pressure differences the air leakage characteristics of a building envelope can be evaluated.

The standard describes the significance and use of the test method, the apparatus required to perform the test, and the measurement and analytical procedures. Hazards involved in making pressurization measurements are noted, and a standard reporting format for the tests is presented.

5.2.6. USA Standard ASTM E 783-84

This standard method deals with the determination of the resistance of installed exterior windows and doors to air leakage resulting from static pressure differences. The method is applicable to window and door assemblies only. However, with adaption, the method can be used to determine the leakage through openings between the window or door assemblies and adjacent construction. A test consists of sealing a chamber to cover the interior or exterior face of a test specimen, supplying air to or exhausting air from the chamber at a rate required to maintain a specified static pressure across the specimen, and measuring the resultant air flow through the specimen.

This test method is similar to the Nordic Component Leakage method described in Section 5.2.3. In this case however a second fan is not used to balance the pressure between the collection chamber and the room containing the component. Therefore the extraneous leakage through the collecting chamber must be evaluated before conducting the leakage test on the specimen.

The calibration procedure, which consists of sealing the specimen with a sheet of polythene film and performing a pressure test, is described in detail in the document. The document also contains sections dealing with the significance and use of the test methods, the apparatus required to perform the test, the preparation of the test specimen and the measurement procedure.

Calculations and the expression of the final results are examined in detail. Safety precautions and measurement accuracy are addressed and a Standard reporting format for the tests is presented.

5.2.7 ISO Draft Standard DP 9972

This International Standards Organisation (ISO) standard (in draft form at time of publication of this document) addresses the use of the mechanical pressurization or depressurization of a building or building component. It describes techniques for measuring the resulting air flow rates at given indoor-outdoor static pressure differences. From the relationship between air flow rates and pressure differences, the air leakage characteristics of a building envelope can be evaluated.

This document is applicable to small temperature differentials and low wind pressure conditions. For tests conducted in the field, it must be recognised that field conditions may be less than ideal. Nevertheless, strong winds and large indoor-outdoor temperature differentials should be avoided. The proper use of this standard requires a knowledge of the principals of air flow and pressure measurements.

This proposed standard is intended for the measurement of the air tightness of building envelopes of single zone buildings. For the purpose of this standard, many multi-zone buildings can be treated as single-zone buildings by opening interior doors or by inducing equal pressures in adjacent zones.

results of the field measurements are not intended to characterize the air leakage of an isolated component but the air leakage of the component and its junction with the building envelope under given conditions of installation.

The standard has sections dealing with the apparatus required for the test, the preparation of the building, the measurement procedure, data analysis and accuracy. A standard reporting format for the test is included.

5.2.8 Comparison of Airtightness Measurement Standards

Several of the standards discussed above deal with the evaluation of the airtightness of the entire building envelope. Table 5.2.2 presents a comparison of some of the salient features of these standards.

The parameters compared are:

Recommended fan flow capacity

The fan used must have the capacity to produce the flow rates and pressure differentials required by the standard. Several standards give guidance as to the flow rates required to perform the test.

Pressure tap location

All standards require a pressure tap within the building and in order to evaluate the pressure difference across the envelope, pressure tap(s) must also be made outside the building shell. Standards vary in the number and location of pressure tap(s) specified.

Differential pressure range

The specified pressure differential across the building envelope varies both in direction and range. All standards however encompass the range 0-50 Pa in either over pressure or under pressure.

Limiting conditions

Natural fluctuating pressure differences across the envelope, caused by wind and temperature effects, affect the accuracy of fan pressurization tests. Several standards place limits on natural pressure difference, wind speed or temperature difference. If these limits are exceeded then the results of the measurement may be invalid.

TABLE 5.2.2. COMPARISON OF AIRTIGHTNESS MEASUREMENT STANDARDS

Standard	Recommended Fan Flow Capacity	Pressure Tap Location	Differential Pressure Range	Limiting Conditions	Expression of Results	Accuracy
CAN/CGSB –149.10-M86	Maximum 1.5–2.5 m^3s^{-1}	At least four taps around building leading to an averaging container	0–50 Pa underpressure	Windspeed < 5.6 ms^{-1}	Equivalent leakage area	Air flow ± 5% △ P ± 2 Pa
NEN 2686	Maximum 1.2 m^3s^{-1}	One tap at building facade	15–100 Pa overpressure or underpressure	Natural △ P across envelope < 5Pa usually windspeed < 6 ms^{-1}	Flow coefficients Flow rate at 1 and 10 Pa in m^3s^{-1}	Airflow ± 5% △ P ± 5%
SS 02 15 51	Sufficient to produce △ P of 55 Pa	One tap 10 m from building ending in a T-piece	0–55 Pa over pressure and underpressure	Windspeed < 6 ms^{-1} 10 m from building	Air change rate at 50 Pa	Airflow ± 6% △ P ± 3 Pa overall ± 10%
E779-87	Not stated	One tap location not stated	12.5–75 Pa overpressure or underpressure	Ideal windspeed < 2 ms^{-1} temperature 5–35°C	Plot of flow against △ P Equivalent leakage area	Airflow ± 6% △ P ± 2.5 Pa
DP9972	Sufficient to produce △ P of 60 Pa	Ideally near neutral plane	10–60 Pa overpressure or underpressure	Natural △ P across envelope < 3 Pa	Flow coefficients	Airflow ± 5% △ P ± 5%

Expression of results

Each standard requires the final results of the test to be expressed in a slightly different form. This is important when comparing the results of tests performed in compliance with individual standards.

Accuracy

Stated accuracy requirements for each standard focus on measurements of air flow rate and pressure difference across the building envelope.

In addition to the specific points described above, standards also vary in building preparation requirements. This factor should also be taken into account if comparing the results of tests performed to comply with a specific standard.

CHAPTER 6: Detailed Description of Measurement Techniques

CHAPTER 6 DETAILED DESCRIPTION OF MEASUREMENT TECHNIQUES

This Chapter describes several measurement techniques in detail. Each description is presented in such a way that specific details can be easily located and the inter-comparision of techniques may be readily performed.

For each technique the description is divided into the following sections.

1. TYPE OF TECHNIQUE

The name of the technique is given, the parameters which are evaluated presented, and the principles behind their measurement described.

2. RANGE OF APPLICATION

This section covers the situations in which the technique has been applied and any potential limitation to its use are noted.

3. EQUIPMENT AND INSTRUMENTATION

The equipment required to perform the measurements is listed and brief descriptions are given. This section is cross-referenced to Chapter 7, which contains more detailed information about selected instruments.

4. SETTING UP AND OPERATING DETAILS

Preparing the measurement site, placing the equipment in the correct location and the procedure for making the measurements are described.

5. PRESENTATION OF RESULTS

This section describes the analysis of the initial data and the presentation of the final results.

6. MEASUREMENT ACCURACY

Accuracy is a vital factor in the selection of any measurement technique. Calibration procedures, comparison with other techniques, and the accuracy of individual instruments are examined.

7. COMMENTS

This section presents the opportunity for points specific to the technique, which have not been examined in previous sections, to be discussed.

8. AVAILABILITY OF MEASUREMENT SYSTEM

It is recommended that the Air Infiltration and Ventilation Centre be used as a first point of contact for the acquisition of further information about specific techniques. However this section indicates the availability of the measurement system and presents useful contact addresses.

References are presented at the end of each Section.

6.1.1 TYPE OF TECHNIQUE

TRACER GAS DECAY RATE - SITE ANALYSIS

Parameter(s) Evaluated

Air change rate at a single point in a building.

Measurement Principle

A single quantity of tracer gas is released and mixed with the air within a building. The change in tracer concentration with time is monitored. The tracer is removed from the building by the ventilation air and, ideally, the concentration will show a negative exponential decay. By examining this decay the air change rate of the building can be evaluated. Section 2.1.1 gives a full treatment of the mathematics required to perform this evaluation.

6.1.2 RANGE OF APPLICATION

This method is suited to situations where a rapid "one off" measurement of the air change rate is needed. The setting up procedure is relatively simple and a minimum of equipment is required. However the limitations concomitant with the simplicity of this technique must be noted. By only measuring the tracer concentration at a single point it is assumed that the evaluated air change rate at this point is representative of the space as a whole. This may only be true in the case of small spaces, and where the air and tracer are well mixed (see Section 2.1.4 for a discussion on mixing). Therefore inferences about the ventilation behaviour of the building as a whole, especially large multi-zone buildings, must be treated with caution.

6.1.3 EQUIPMENT AND INSTRUMENTATION

This basic technique relies upon only a single tracer gas and a suitable analyser. Several combinations of tracer and analyser can be used. One combination will be described here, but the use of other tracers and analysers should not be precluded.

A much used and well documented combination for this type of measurement is sulphur hexafluoride tracer gas used with a gas chromatograph electron capture detector. An account of the properties of tracer gases is given in Section 4.1, and a description of this gas analysis method is provided in Section 4.2.1.

6.1.4 SETTING UP AND OPERATING DETAILS

The building should be prepared so as to correspond to the desired measurement situation.

Tracer Gas Release

A small amount of sulphur hexafluoride is released into the test space. The volume of tracer required will depend upon the detection range of the gas analyser and the volume of the building. A suitable initial concentration for an electron capture detector is 5-15 parts sulphur hexafluoride in 10^9 parts of air. This is 5-15 mls of pure sulphur hexafluoride per 1000 m^3 of building volume.

Portable desk fans can be used to aid the mixing of the tracer in order to obtain a uniform concentration of tracer throughout the enclosure. If the tracer is discharged into the supply duct of a mechanical ventilation system, then any area served by the duct will be dosed with tracer.

In buildings with a large internal volume it may be necessary to discharge large amounts of tracer. If this is the case then the following method may be used: the operator works out a zig-zag or circular path through the area which will give good coverage of the building. The time taken to walk along the path is noted. The amount of gas required to dose the area is evaluated (from knowledge of the building volume and the required initial concentration), and the gas flow rate needed to discharge that volume of gas in the time taken to walk along the path calculated. The cylinder is set to discharge the gas at the required rate and the operator walks along the path carrying the discharge cylinder. Some mixing of air and tracer will occur as a consequence of the movement of the operator through the building.

Sampling the Air Tracer Mixture

This section describes the sampling of the air tracer mixture using a specific gas chromatograph/electron capture detector. However the same basic principle applies whatever analyser is used. The aim of the sampling process is to obtain values of the tracer gas concentration at several known time points after the gas is released.

The chromatograph/detector is operated in "sample mode"; this takes a discrete volume of air and evaluates the concentration of sulphur hexafluoride in it to a high order of accuracy.

Two methods of recording concentration data can be used. The detector contains an analogue output meter and stopwatch; hence times and concentrations can be written down by the operator.

Alternatively the detector output can be linked to a chart recorder via a standard output jack. The chart recorder should have a time base facility. The operator then has to only operate the sample valve and values for the concentration and time are automatically recorded on the chart.

Which ever way the concentration is recorded the sampling process is the same in each case. The sample valve is turned and held open for two seconds and then closed. This sends an air sample down the chromatograph column towards the detector. About five seconds later a large peak will show on the meter and chart. This is caused by oxygen in the air sample reaching the detector. Oxygen is an electron capturing gas. After about 20-30 seconds the sulphur hexafluoride peak appears. The concentration of tracer can be evaluated from either the height of the peak or the area under the peak. The sample valve is then operated at regular timed intervals (1-2 minutes) until sufficient data points are obtained.

Measurement Duration

A good estimate of the air change rate can be obtained in 10-20 minutes. This enables a reasonable number of points to be obtained for the decay curve and line fit. The graphical evaluation of air change rate from decay data has already been illustrated in Figure 2.1.1. As this technique assumes that the air change rate is constant over the measurement period, care must be taken when analysing the data to ensure that this has been the case. If, however, the air change rate alters abruptly during the measurement period, then this is reflected as a rapid change in the decay curve. In this case the measurement period may have to be subdivided and separate analysis performed on each true exponential decay curve.

6.1.5 PRESENTATION OF RESULTS

This technique is often used as an investigative tool in troubleshooting situations. Hence the presentation of results may be single values of the air change rate. However an air change rate presented by itself provides little information about the ventilation behaviour of the building. This is due to the fact that an air change rate is a variable parameter depending upon a variety of constructional, climatic and behavioural factors.

When an air change rate is given, some information about the building, ventilation system and climate should also be provided. A guideline to the minimum amount of additional information required to enable an adequate interpretation of air change rate measurements to be made, is presented in Section 2.3.

6.1.6 MEASUREMENT ACCURACY

In general the accuracy of this technique has been checked in a sealed chamber with controlled air change rates, and was found to be reliable and reproducible. The detector described here has quoted accuracy of ±2%.

6.1.7 COMMENTS

This simple technique is ideal for one off measurements of air change rates in a variety of buildings. While noting its limitations it has the advantage of producing reliable results in a short period of time with minimum equipment. Although automated decay systems have been produced (see, for example, Hartmann and Muhlebach [1981]) this reduces the simplicity of use which makes this technique attractive to non-specialist consultants and engineers.

6.1.8 AVAILABILITY OF MEASUREMENT SYSTEM

The gas analyser described here is readily available complete with instructions for its operation and use for this type of measurement.

Further information about this detector is presented in Section 7.1

Sulphur hexafluoride for use as a tracer gas is available in various degrees of purity from several manufacturers worldwide. It is suggested that national trade directories be consulted in order to locate the nearest supplier of this or any other tracer gas.

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Air Leakage Measurements by the Tracer Dilution method - A review.
Building Air Change Rate and Infiltration Measurements, ASTM STP 719, pp36-49, 1980.

In Text

Hartmann, P., Muhlebach, H. [1980].
Automatic Measurements of Air Change Rates (Decay Method) In Small Residential Buildings Without Any Forced-Air-Heating System.
1st AIVC Conference - Air Infiltration Instrumentation and Measuring Techniques, pp87-102, Windsor, United Kingdom, 1980.

6.2.1 TYPE OF TECHNIQUE

TRACER GAS DECAY RATE - GRAB SAMPLING (BOTTLES)

Parameter(s) Evaluated

Air change rate of dwellings or larger buildings over a 2-3 hour period.

Measurement Principle

This technique uses the measured decay rate of a tracer gas to evaluate the air change rate of a building. On site gas injection and sampling is performed using flexible plastic bottles. Air samples obtained in this manner are returned to a central laboratory. They are then analysed for tracer gas concentration and the air change rate is evaluated from the decay data.

6.2.2 RANGE OF APPLICATION

This technique has been used extensively for the evaluation of air change rates in dwellings. It has also been extended for use in larger multistorey buildings such as apartment blocks. The technique is ideally suited to the simultaneous examination of a large number of buildings, this technique allows tracer gas injection and sampling to be performed by non-technical personnel.

6.2.3 EQUIPMENT AND INSTRUMENTATION

The equipment can be divided into two categories:

- Field deployed injection and sampling bottles.

- Laboratory based analysis equipment.

Field Equipment

The tracer gas (sulphur hexafluoride is in common use for this technique and will be discussed here) is injected and sampled using modified 500 ml flexible polyethylene bottles. Modification involves drilling a 6 mm diameter hole through the plastic cap and adding a 2 mm thick natural rubber gasket. Several bottles are required to make a test, e.g. for a dwelling - one for injection and five for sampling. In order to avoid cross-contamination, the injection bottle must be clearly marked and never used for sampling. Each sampling bottle must also be marked to enable it to be uniquely identified. A simple numbering system is adequate. It may be necessary to aid tracer gas mixing. If so, this can be performed using paddles or small electric fans.

These must also be taken to the measurement site.

Laboratory Equipment

The laboratory instrumentation essentially consists of a gas analyser. In this case a specific analyser i.e. a gas analyser chromatograph electron capture detector will be discussed. This commercially available unit (see Section 7.1) is specially adapted to enable bottle samples to be analysed for sulphur hexafluoride concentration. The chromatograph sample line is fitted with a small hypodermic needle. This is inserted into the rubber gasket which acts as a septum. Air is withdrawn from the bottle at a controlled rate measured by a sensitive flow meter and needle valve. Pressure is exerted on the bottle to avoid injection of room air. This is achieved by a weighted clamp which presses down on the bottle under examination. A sample of air is drawn into the chromatograph column where the oxygen and sulphur hexafluoride tracer are separated before they reach the electron capture detector. The concentration of tracer gas can be evaluated from the output of the detector.

6.2.4 SETTING UP AND OPERATING DETAILS

This section describes the procedure for obtaining the air change rate of a dwelling over a period of about 3 hours. The basic principles of the operation are shown and this technique may be applied to buildings other than dwellings.

Injection and Mixing

A clearly marked polythene bottle is charged with tracer in the laboratory. This is taken, along with five sample bottles, to the measurement location. The tracer is then released into the building. This is easily performed by loosening the cap and walking around the building while gently squeezing the bottle.

Air and tracer should then be allowed to mix. If the dwelling has a warm air heating system, this may be used to promote mixing although it may be desirable to switch off such systems during tracer sampling. Mixing may also be aided by small electric fans placed in the building. These should be stopped before gas sampling commences.

Sampling

After the initial mixing period (approximately half an hour), the first sample bottle can be filled with air from the measurement site. Squeezing the bottle first from one side and then 90 degrees away for 10 squeezes adequately fills the bottle with air from the given location. The cap should then be firmly replaced on the bottle. From then on, further samples can be taken at given time intervals. A sample interval of half an hour is often used.

The bottles should be clearly numbered and the time and location of samples must be recorded. A simple logging sheet is useful for this purpose. Wind, temperature and other relevant data can also be recorded on this sheet.

Synchronous bottle samples may be taken at several locations in the same building. This could be used, for example, to examine air change rates for individual floors of a multistorey building. If the personnel are available, simultaneous sampling can be performed in many buildings in the same area. This would allow the air change rates of those buildings under similar weather conditions to be compared.

Sample bottles are then returned to the laboratory for analysis. The concentration of sulphur hexafluoride in each bottle is evaluated using the chromatograph/electron capture device. Several individual measurements of concentration may be obtained from each bottle and a mean value obtained. Because the bottles are fitted with the rubber septum, they can be reused many times, providing the air from the previous sample is fully discharged.

6.2.5 PRESENTATION OF RESULTS

The raw concentration data obtained from the analysis can be plotted against time. This type of plot indicates the exponential nature of the decay curve and spurious data points can be spotted immediately.

Further analysis is performed using a computer or hand-held calculator. The log of the concentration is plotted against time and a least square fit routine applied. The air change rate, together with the statistics of the regression analysis, are printed out by the computer.

If tracer injection and sampling takes place simultaneously at several measurement sites in the same general area, the inter-comparison of many buildings under the same weather conditions can be performed. This is illustrated in Figure 6.2.1. Here simultaneous air change measurements were made in 15 nominally identical houses and the houses are arranged from left to right in increasing air change rate order.

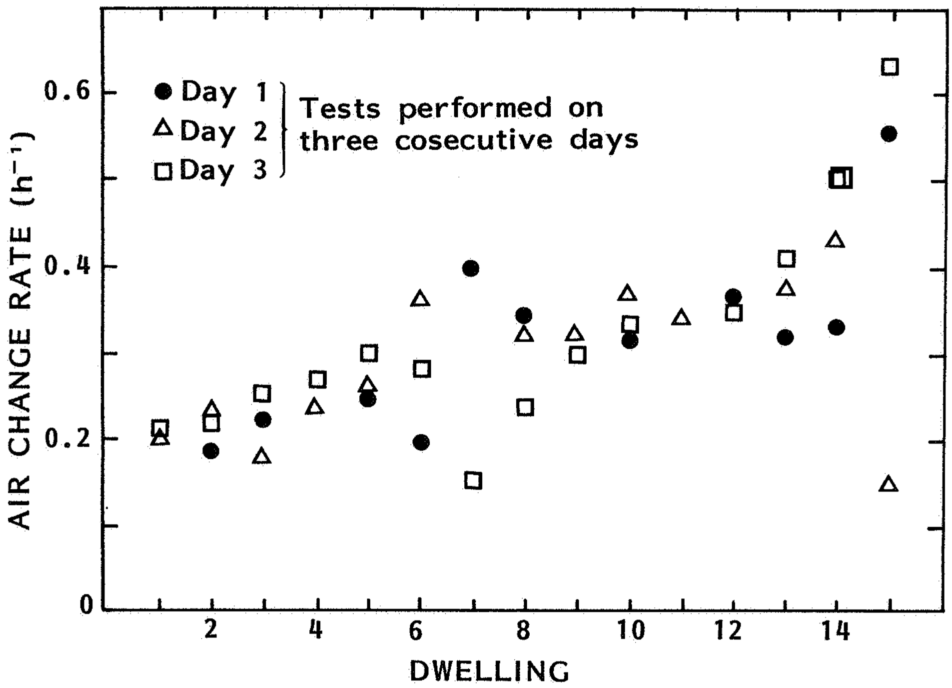

Figure 6.2.1 **Simultaneous measurement of 15 dwellings (after HARRJE [1982])**

6.2.6 MEASUREMENT ACCURACY

This technique is susceptible to both site and laboratory errors. In large buildings in particular, mixing may not be perfect. Therefore single concentration measurements may not reflect the test space as a whole. This problem may be overcome by taking samples at several locations. If samples are taken by non-technical personnel, then problems may arise unless adequate instruction is provided.

The air change rate of a building is dependent upon the weather, occupant behaviour and mechanical ventilation systems. In order to keep the air change rate as constant as possible during the measurement period, the condition of the building (e.g. windows closed, mechanical ventilation system off) should not be changed during the test. The weather is not so easy to control but, with care, measurements can be made during periods when it is least changeable. If samples are taken over a period of time, then the air change rate from individual pairs of samples can be obtained and any variation with time evaluated.

Samples are transported, often some distance, to a laboratory site. Therefore, if there was any change in tracer concentration within the bottle during transportation, then this could affect the measurement results. Laboratory tests have shown that, providing the correct measurement procedure is followed, then there are no significant effects from this potential source of error.

Laboratory errors are also minimised by taking several readings of the concentration from each bottle. The calibration of detection equipment is eased by the fact that only relative, not absolute, concentration levels need be found. It can be concluded that, providing sufficient care is taken making measurements under favourable conditions, this technique provides an accurate method of measuring the air change rate of a variety of buildings.

6.2.7 COMMENTS

For single family homes, the technique is simple enough so that homeowners can easily obtain samples and return them to the laboratory for analysis. This technique is not confined to the use of flexible plastic bottles. Syringes and air bags have both been used to collect air samples (see, for example, Grot [1980]).

6.2.8 AVAILABILITY OF MEASUREMENT SYSTEM

The essential component of this system is the gas analyser. The chromatograph/electron capture detector described here is a commercially available unit, (see Section 7.1).

The following organisation has had experience with this technique.

D. Harrje
Center for Energy & Environmental Studies
Princeton University
Princeton
NJ 08544
USA

Tel: 609 452 5190/5467

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Harrje, D T, Gadsby, K, Linteris, G. [1982].
Sampling for Air Exchange Rates in a Variety of Buildings.
ASHRAE Transactions, Vol 88, Pt 1, 1982.

In Text

Grot, R.A. [1980].
A Low Cost Method for Measuring Air Infiltration Rates in a Large Sample of Dwellings.
Building Air Change Rate and Infiltration Measurements ASTM STP 719, pp50-59, 1980.

6.3.1 TYPE OF TECHNIQUE

TRACER GAS DECAY RATE - GRAB SAMPLING (DETECTOR TUBES).

Parameter(s) Evaluated

This technique enables the total building air flow rate to be evaluated.

Measurement Principle

Carbon dioxide is used as a tracer gas and its variation in concentration with time is monitored on site using detector tubes. In occupied spaces a simple exponential decay of the tracer does not occur. This is due to the carbon dioxide exhaled by the occupants. Hence it is not possible to use the standard decay curve method, as described in Section 2.1.1, to evaluate the air change rate. Instead a slightly more complex analysis must be utilised. This is presented below.

The continuity equation can be presented as:

$$V\frac{dc_{(t)}}{dt} = -Q\,[C_{(t)} - C_e] + F_{(t)} \qquad [6.3.1]$$

Where

V = Building volume, m^3

$C_{(t)}$ = Concentration of tracer at time t

Q = Specific air flow rate, m^3s^{-1}

C_e = External concentration of tracer

$F_{(t)}$ = Production rate of CO_2 by occupants

If it is assumed that Q is time independent over the period of the measurement then both sides of Equation 6.3.1 can be integrated over the total measurement period, and then arranged to give:

$$Q = V\,\frac{\left[\displaystyle\int_{t=0}^{t=t_m}\frac{F_{(t)}}{V}dt - \int_{t=0}^{t=t_m} dC_{(t)}\right]}{\displaystyle\int_{t=0}^{t=t_m}[C_{(t)} - C_e]\,dt} \qquad [6.3.2]$$

Where

t_m = Total measurement period

Assuming that the production rate of carbon dioxide by the occupant is constant, then this gives:

$$Q = \frac{V\,[C_{t=0} - C_{t=tm} + \frac{F\,t_m}{V}]}{\int_{t=0}^{t=t_m} [C_{(t)} - C_e]\,dt} \qquad [6.3.3]$$

If n samples of the tracer concentration are taken with a constant time period between each sample, then the integral in Equation 6.3.3 can be evaluated as:

$$\int_{t=0}^{t=t_m} [C_{(t)} - C_e]\,dt = 0.5\,(C_1 + C_n)\,\Delta t + \sum_{i=2}^{n-1} C_i\,\Delta t \qquad [6.3.4]$$

Where

n = Number of samples of tracer concentration

Δt = Time interval between samples

Therefore by using Equations 6.3.3 and 6.3.4 the air flow rate can be calculated.

6.3.2 RANGE OF APPLICATION

This technique has, been tested in a mechanically ventilated controlled flow rate test house, with a maximum of two occupants. Site work had also been performed in dwellings with mechanical extract ventilation.

6.3.3 EQUIPMENT AND INSTRUMENTATION

Two essential items are required for this technique. These are a source of carbon dioxide and a set of detector tubes with bellows. The carbon dioxide source must be capable of producing an initial concentration of tracer in the test building of approximately 2000 ppm (0.2% by volume). This is easily achieved by releasing a short burst of carbon dioxide from a gas cylinder.

Mixing fans may be used in order to obtain a uniform concentration of carbon dioxide throughout the test space.

Tracer concentrations are obtained using the detector tubes. These are glass tubes packed with a selective solid absorbent which gives a colour reaction with the carbon dioxide. The tubes used are sensitive to carbon dioxide in the 0.01-0.30% range. Tubes as supplied by the manufacturer are sealed at both ends. To make a measurement the seals are broken, one end of the tube (the correct end is indicated on the tube), is inserted into a pair of specially designed hand bellows, the other end being left open to sample the air tracer mixture. Figure 6.3.1 shows a tube and bellows being used to make a measurement.

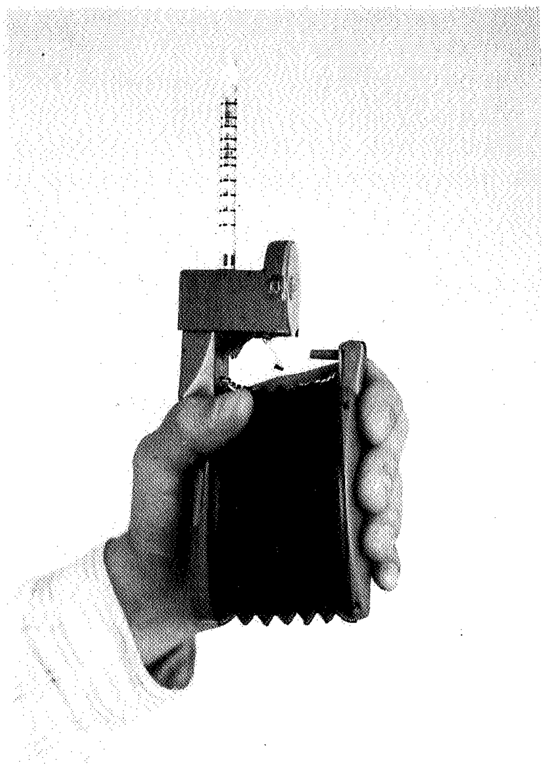

Figure 6.3.1 Detector tube and bellows for carbon dioxide sampling

By making the prescribed number of strokes of the hand held bellows the correct amount of air is drawn through the tube. This enables the carbon dioxide evaluation to be made. The glass tube has graduation marks on it, and the length of the discolouration caused by the reaction indicates the concentration of carbon dioxide in the room air. Detector tubes can only be used once and must be discarded after each sample taken.

6.3.4 SETTING UP AND OPERATING DETAILS

Before the measurement commences the volume of the building and the occupancy level must be noted. Both of these parameters are required in order to be able to calculate the air change rate. The tracer gas is then released and small mixing fans can be used to maintain a constant spatial concentration. An ideal starting concentration is in the region of 2000 ppm.

After release the tracer concentration should be monitored at several evenly spaced time points. A total of five points at 15 minute intervals has been found to be adequate for this purpose.

An individual measurement may take some time to perform. Typically ten strokes of the hand held bellows are required to draw sufficient air through the tube. Each stroke may take in the region of 15-25 seconds to perform. Hence the "spot" measurement of concentration is actually obtained over a period of a few minutes. This, however, should not create difficulties providing consistent measurement and time logging procedures are adopted.

6.3.5 PRESENTATION OF RESULTS

Results from this technique can be initially presented as a plot of tracer concentration against time. Figure 6.3.2, for example, shows this type of plot for data obtained in a mechanically ventilated test house. The dashed line represents the exponential decay of concentration which would be expected with no occupant production of carbon dioxide perfect mixing. The actual decay (shown by the cross points) is far from exponential and therefore Equations 6.3.3 and 6.3.4 must be utilised to evaluate the air flow rate. The calculation procedure is simple enough to be performed by hand. The circle points on Figure 6.3.2 are concentrations measured with an infra-red gas analyser. Section 6.3.6 presents the reasons for making these measurements.

6.3.6 MEASUREMENT ACCURACY

This technique has been assessed for accuracy in a 176 m^3 test house with controlled mechanical extract ventilation. In the test house air was extracted from the kitchen and bathroom and the intake of air was through openings in the living room and bedroom. Extract flow rates were measured to an accuracy of 2-3% using orifice plates. Tests were performed at two nominal flow rates, and the effect of occupancy was examined i.e., 0, 1 and 2 occupants.

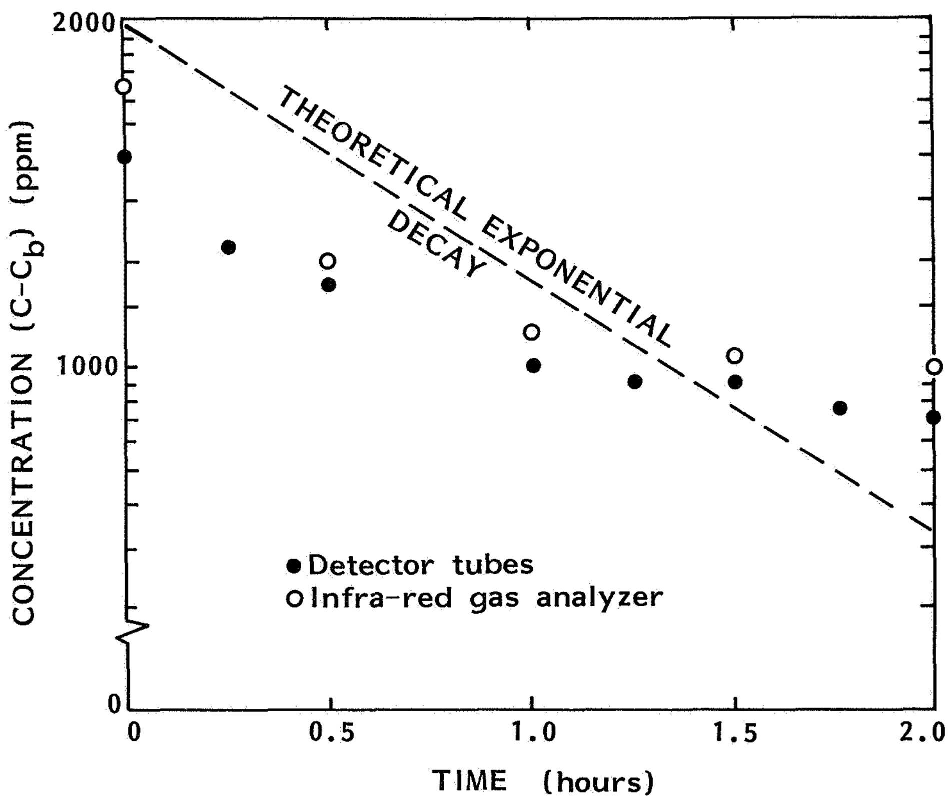

Figure 6.3.2 **Carbon dioxide concentration v time for a mechanically ventilated test house (after SANDBERG and SUNDBERG [1987])**

Tracer concentrations were recorded with the detector tubes and, for comparison, with a standard infra-red gas analyser (see Section 7.2). Table 6.3.1 shows the results of these tests expressed as air changes per hour. From this table it can be seen that the detector tubes compare well with the established infra-red gas analysis method. More importantly they give satisfactory results (considering the trade off between accuracy and expense) when compared against the absolute flow rates as measured by the orifice plates. When assessing these tests it must be noted that all tracer concentrations were recorded in the living room of the house, and perhaps better results could have been obtained if concentrations were measured in a room where the main part of the air leaves the house.

6.3.7 COMMENTS

This technique also requires estimates of the metabolic carbon dioxide production rates to be made. In the validation tests described in Section 6.3.6 the carbon

TABLE 6.3.1. COMPARISON OF MEASURED FLOW RATES IN A MECHANICALLY VENTILATED TEST HOUSE

OCCUPANY LEVEL	NOMINAL FLOW RATE HOUSE VOLUMES/h	MEASURED FLOW RATE HOUSE VOLUMES/h	
		INFRA-RED GAS ANALYZER	DETECTOR TUBES
UNOCCUPIED	0.54	0.58 (+17%)	0.52 (-4%)
	0.96	0.88 (-8%)	0.79 (-17%)
ONE PERSON IN THE LIVING ROOM	0.54	0.55 (+2%)	0.50 (-7%)
	0.96	1.02 (+7%)	0.87 (-8%)
ONE PERSON IN THE SLEEPING ROOM	0.54	0.57 (+5%)	0.51 (-5%)
	0.96	1.02 (+7%)	0.89 (-6%)
TWO PERSONS IN THE HOUSE	0.54	0.57 (+6%)	0.44 (-18%)
	0.96	1.22 (+27%)	1.12 (+17%)

dioxide production rate was set to 0.35 litres per minute per person. In general carbon dioxide production rates can be found in any standard text book on hygiene. Detector tubes are available for evaluating a wide variety of gases. For further information contact the company given in Section 6.3.8.

6.3.8 AVAILABILITY OF MEASUREMENT SYSTEM

Gas detector tubes are available from:

Dragerwerk AG
Lubeck
Federal Republic of Germany

Tel: Int +49 451 882-0
Telex: 26807-0

This company name has become synonymous with this type of detector tube. Although based in Germany the company has suppliers world wide.

Further information about this technique can be obtained from.

Mats Sandberg
The National Swedish Institute for Building Research
Box 785
S-801 29 Gavle
Sweden

Tel: 026-10 0220

REFERENCES

Specific to Technique

Sandberg, M.and Sundberg, J. [1987].
The Use of Detector Tubes with Carbon Dioxide Tracer Gas.
Air Infiltration Review, Vol 8, No 3, pp6-7, May 1987.

6.4.1 TYPE OF TECHNIQUE

TRACER GAS CONSTANT EMISSION RATE - PASSIVE SAMPLING

Parameter(s) Evaluated

Long term average air infiltration rates and interzonal air flows in occupied buildings.

Measurement Principle

Passive sources are used to emit tracer gas at a constant rate. The average concentration of tracer gas over a given period is measured using passive samplers. This concentration is taken to be equal to the emission rate of the tracer gas source, divided by the air infiltration rate. Extending this principle to a multi-zone concept, a different type of tracer gas source is deployed in each zone of a building. This allows the calculation of the infiltration rate in each zone and the air exchange rates between each zone. The basic principles of this method are presented in Section 2.1.2.

6.4.2 RANGE OF APPLICATION

This air infiltration measurement system has been used to make more than 5000 home and commercial building ventilation determinations. Most of the measurements have treated the buildings as two-zone types with single-zone and three-zone measurements being the next most prevalent cases, respectively. The technique has been applied in buildings of all sizes, from small homes to large commercial buildings.

6.4.3 EQUIPMENT AND INSTRUMENTATION

General Description

The equipment required can be divided into two categories:

- Field deployed tracer emitters and samplers.

- Laboratory based analysis equipment.

Field Equipment

The tracer source

Fully fluorinated organic compounds of the perfluoroalkylcycloalkane family are used as the tracer gases (PFTs).

The PFT source is a small permeation device which, at a known temperature, emits a constant rate of PFT vapour through a silicone rubber plug connected to a source of PFT liquid (see Figure 6.4.1).

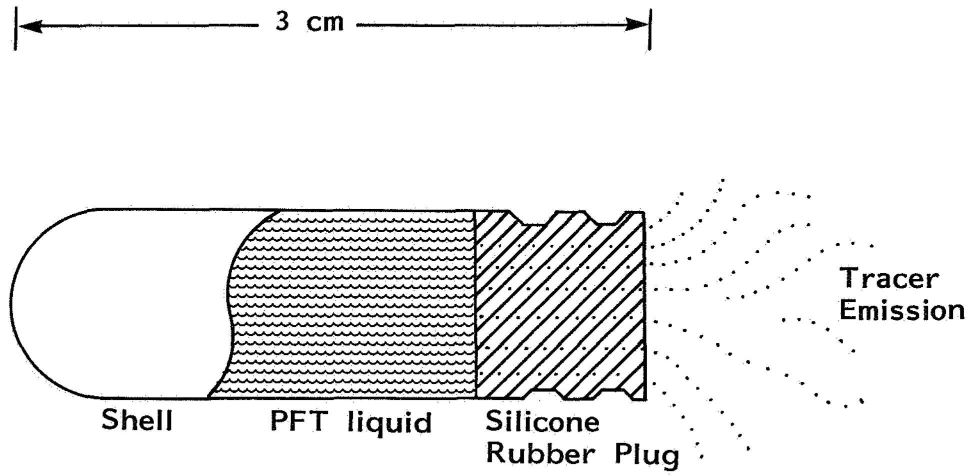

Figure 6.4.1 Schematic of PFT source

Aluminium shells 32mm long x 6.6mm inside diameter are flared slightly to facilitate the insertion of the oversized silicon rubber plugs (12.7mm long x 7mm diameter). The shells are then lubricated, swabbed with a solution of 5% silicone grease in ethyl acetate, and air-dried in an inverted position to concentrate the lubricant at the opening. A code number is engraved onto the shell for identification of the PFT source, silicone rubber plug type and number of the source.

The shells are filled with exactly 0.4 ml of the appropriate PFT liquid, using an automatic pipette. Table 6.4.1 lists the presently used PFTs. The pre-cut plugs are inserted, pressed flush with the end and crimped into the shell.

The PFT sources can be produced in large numbers - around 500 per person-week. For every fifty made, one is kept in a constant temperature chamber (25 °C) and periodically (for example, monthly) weighed on a high precision balance to determine the gravimetric rate of emission. This can be converted into a volumetric rate using the gas law constant, the molecular weight, and the composition of the tracer (to account for impurities).

TABLE 6.4.1. PER FLUORO TRACER INFORMATION

PFT	MOLECULAR WEIGHT	LIFETIME (YEARS)[1]	AMBIENT BACKGROUND CONCENTRATION[2]
Perfluorodimethylcyclobutane (PDCB)	300	2.1–2.9	0.35 fL/L
Perfluoromethylcyclopentane (PMCP)	300	1.9–2.6	2.8 fL/L
Perfluoromethylcyclohexane (PMCH)	350	2.7–4.0	3.6 fL/L
Perfluorodimethylcyclohexane (PDCH)	400	4.3–7.2	25.6 fL/L

[1] Based on an initial 0.4 mL of liquid

[2] fL/L = femtolitres per litre (10^{-15})

The tracer sampler

The gas sampler consists of a glass tube with an adsorbent in the middle (see Figure 6.4.2). The device samples tracer vapours by the principle of passive diffusion. Subsequent thermal desorption and analysis is required to obtain the desired concentration results.

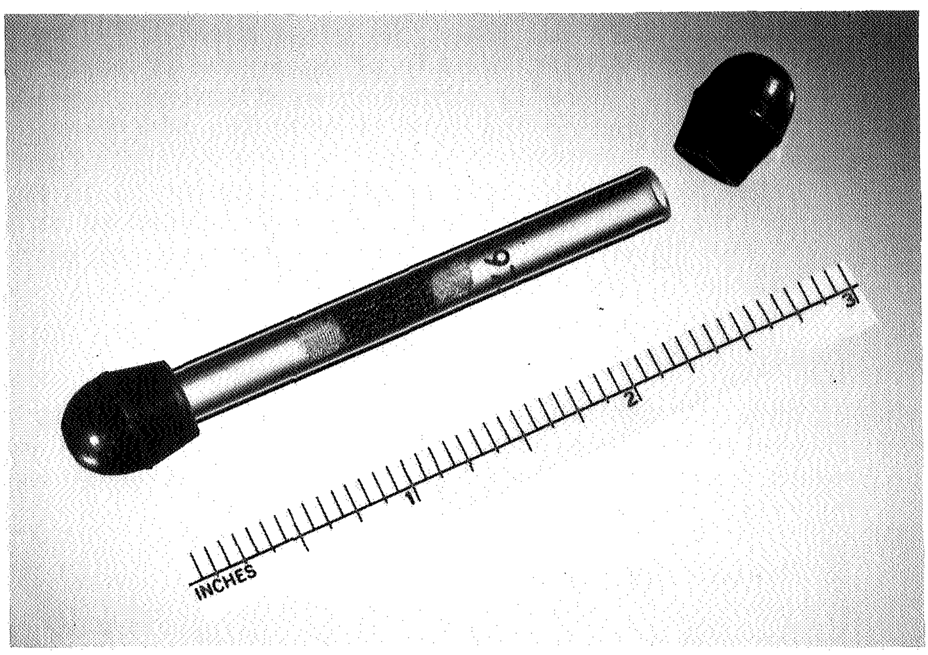

Figure 6.4.2 PFT passive sampler

A glass tube 6.4mm OD x 4mm ID x 6.4 cm long with a 45° taper ground at the ends to about one third of the wall thickness, is cut from conventional pyrex glass tubing. The tubing is selected to have an ID within ± 1.5% of the design value; the length is cut to within ± 0.8 mm. This tolerance is necessary to keep the sampling rate, which is proportional to the cross-sectional area and inversely proportional to the length from the mouth of the glass tube to the surface of the adsorbent bed, within ± 3% precision.

Screens shaped like cups are used to retain the adsorbent material within the glass tube. These are made from stainless steel wire cloth.

A charcoal-like adsorbent is used to "collect" the tracer gas. It is produced in the form of small beads and it is put through a conditioning process before being used as a tracer sampler. It is initially boiled, three times, in distilled water, and any fine dust floating on the surface is decanted off. It is then dried and rolled down a very shallow, inclined plane to separate any shapes which are not nearly perfect spheres. Finally, it is boiled again until the decanted fluid is clear, dried and sieved to a 30-to-50 mesh size.

The glass tubes are cleared using a detergent solution and given a unique identification number. A cupped screen is then pressed into one end of the tube to a depth of 2.75 cm. Then the glass tube is filled using a small cup holding exactly 64 mg of the prepared adsorbent. Finally another cupped screen is placed from the other end of the tube to hold the adsorbent in place.

After initial fabrication of the sampler it is made ready for its first use by being thermally desorbed at 425-450 °C for 10 minutes. The ends are then sealed with specially fabricated polyurethane rubber caps.

<u>Laboratory Analysis Equipment</u>

Only the tracer gas sources and the passive samplers are placed in the building under examination. All analysis of tracer gas concentrations and evaluation of air change rates are performed in the laboratory.

Thermal desorption

The most efficient way of desorbing gases adsorbed on solids is to heat the solid in the presence of a flowing inert gas. This process is known as thermal desorption. One device used for thermal desorption is described below.

The thermal desorption device described here is a special rack which has positions for 23 sample tubes. This device was the one originally used during the development of this technique. Several commercial thermal desorption devices are now available. However, any device used for this process must be capable of reaching a 450 °C desorption temperature. The rack can also be used for the baking stage of the initial conditioning of the sample tubes.

The tubes are heated using resistance wire heating elements consisting of about 10 turns of nicrome wire. The tubes can be heated to 450 °C in 30 seconds, and this temperature is held for another 30 seconds to effect the sample recovery. Tubes are placed into the rack by slipping them through the heating coils (one end of the rack is removed to facilitate this), until they contact the spring-loaded O-ring seal pistons. The removed end, a 25mm square aluminium stock, is replaced, and the eccentric cam compresses the tube ends against the spring-loaded seals. The open 1.59 mm tubing ends are connected to a 24-position Scanivalve rotary valve assembly which has an electrical rotary switch to bring desorption power to the proper tube. The most recent rack design uses a more-preferred double O-ring trapped seal with the sampler slipping through the O-rings.

Gas Chromatograph Assembly

The determination of the concentration of the PFTs collected by the tubes is accomplished with a modified gas chromatograph system. The scheme includes thermal desorption, chemical and physical processing, chromatographic separation and electron capture detector (ECD) determination of the quantity of tracer recovered. A schematic of the latest gas chromatograph (GC) assembly, used for this technique, is shown in Figure 6.4.3.

This detector makes use of the electron-capturing properties of the PFTs. A small, sealed, radioactive source is placed inside an ionisation chamber where it generates a cloud of electrons. When a pulsed voltage is applied across the chamber, a current flows. The sample is introduced to the cell, whereupon electron capturing material reduces the number of electrons and hence the current of gas detected.

The sample is automatically thermally desorbed and passed through a Pd catalyst bed and a pre-cut column before being re-concentrated on an in situ trap. The trap prevents the collection of unwanted low molecular weight constituents, and the pre-cut column prevents the

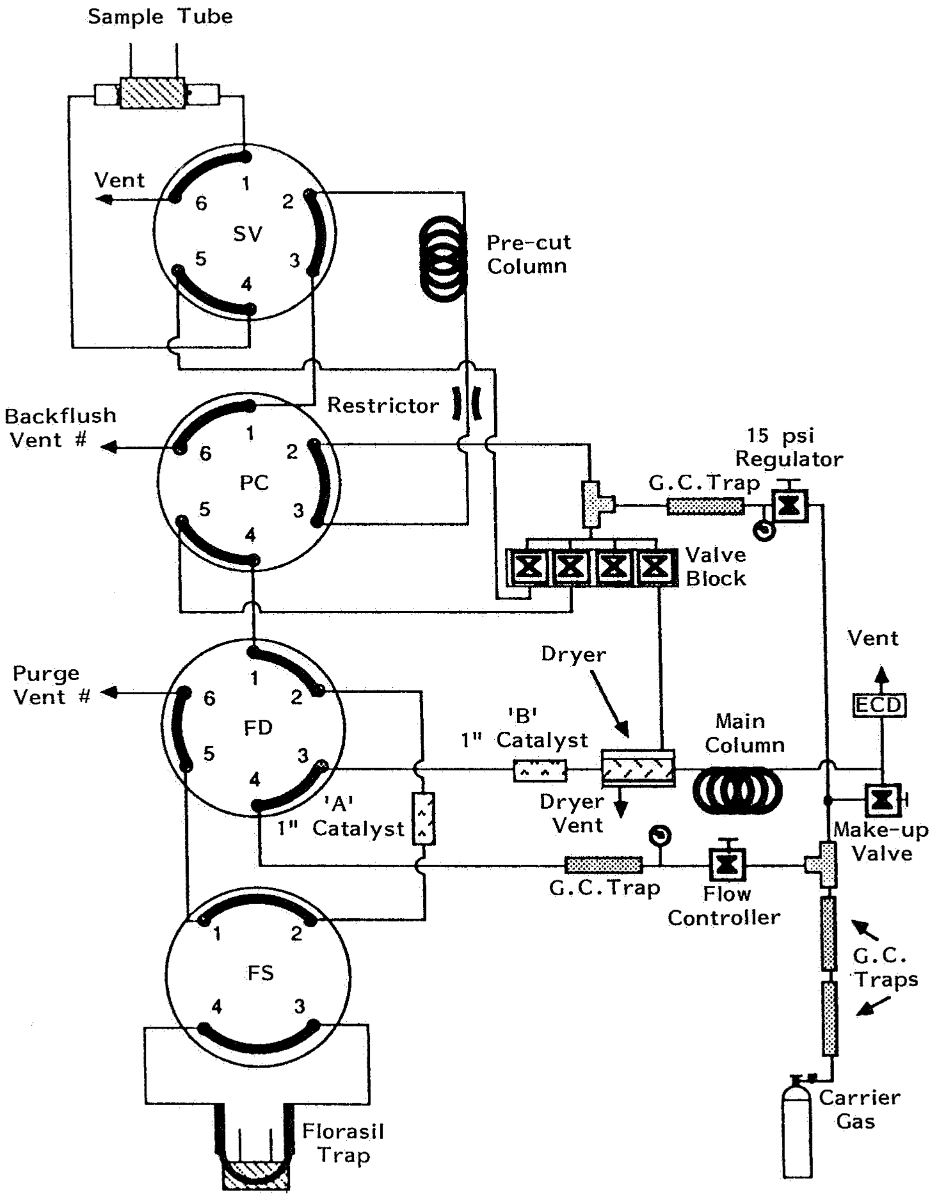

Figure 6.4.3 Schematic of the laboratory GC plumbing. (SV) Sample valve (PC) Pre-cut column backflush valve. (FD) Flow direction valve to isolate the chromatography occuring in the main column from the loading of the next sample. (FS) Florasil trap valve. All valves are shown in their 'off' position.

passage of unwanted high molecular weight constituents. After thermally desorbing the trap, the PFTs are separated in the main column after passing through another Pd catalyst bed and permeation dryer (to remove moisture) and detected in the ECD. Two processes occur during a single cycle; analysis of a previously collected sample and the loading of a new sample onto the trap. At the start of the cycle, the FD valve (see Figure 6.4.3) goes on as well as the Florasil trap valve (FS). Note that all the valves are shown in their "off" position; "on" means the FS valve rotor turns 90 degrees and the others, 60 degrees. Thus, when heat is applied to the FS trap, the adsorbed PFTs are flushed out through catalyst bed "A", catalyst bed "B", the dryer, the main column, and the detector (ECD). The entire process for the last PTCH isomer to elute is under 12 min; the cycle time was set for 12 min.

However, during this time, another sample tube is desorbed, processed, and collected in the trap. For the first 3 min, the sample tube is purged of oxygen by the carrier gas (5% hydrogen in nitrogen). Then both the PC and SV are turned on and heat is applied to the sample tube to sweep the PFTs into the pre-cut column, a 560 mm by 2.9 mm thin-walled stainless steel column packed with Unibeads 2S (Alltech) at 85 °C. The unknown, early-eluting interfering compounds will flow out of purge vent No. 2. Just before the first PFT elutes from the pre-cut column, the FD valve is turned off and the FS trap is opened. This allows the PFTs to be collected in the Florasil trap as they leave the pre-cut column, which is ohmically heated to a higher temperature. When the last PFT component has entered the trap, all the valves go to their off position (at 9.6 min), which allows the pre-cut column to be back flushed at the higher temperature for more than 2 min to eliminate any heavy components.

The pre-cut column system prevents components lighter than the first PFT from seeing the catalyst bed "A" or from entering the trap. Components heavier than the last PFT selected for analysis are also precluded. By tailoring the pre-cut column temperatures, the PFT "window" can be increased or decreased at either the beginning or the end.

The catalyst is important in removing interfering compounds. With this system, the PFT sample passes once through catalyst bed "A" on its way into the trap, once again upon recovery from the trap, and once through catalyst bed "B". This assures a good cleanup of the sample.

6.4.4 SETTING UP AND OPERATING DETAILS

Transportation

In order to avoid contamination, the PFT sources and gas samplers should be separately transported to the measurement site. It is good practice to retain two or three passive samplers as controls, i.e. unopened, in order to verify the absence of contamination during transportation, deployment and storage.

Locating Sources and Samplers

Sources

Each source shell is engraved with a code, the first number of which identifies it as one of the four available PFT types. The sources are usually deployed one per every 46.5 m^3 of living area. Typically, in a single storey home, two sources are placed in the living room - dining room - kitchen area and one in each of the bedrooms (see Figure 6.4.4). The same type of source should be used if the floor is to be treated as a single zone. If the house has a basement, a different PFT type should be used since it is a separate but attached zone. For an open (unfinished) basement, one or two sources may be used; if it is divided into rooms, 2 sources should be used. Ignoring the basement by not including any sources and samplers, or using sources of the same type as the main floor, can result in errors in the determination of the living space ventilation rate.
Alternatively, the main floor of a single storey home can be divided into two zones, the family zone (living room - dining room - kitchen) and the bedroom zone (the bedrooms, bathroom and hall), each tagged with the appropriate number of PFT sources but of different types. With a basement, the house then becomes a three zone study.

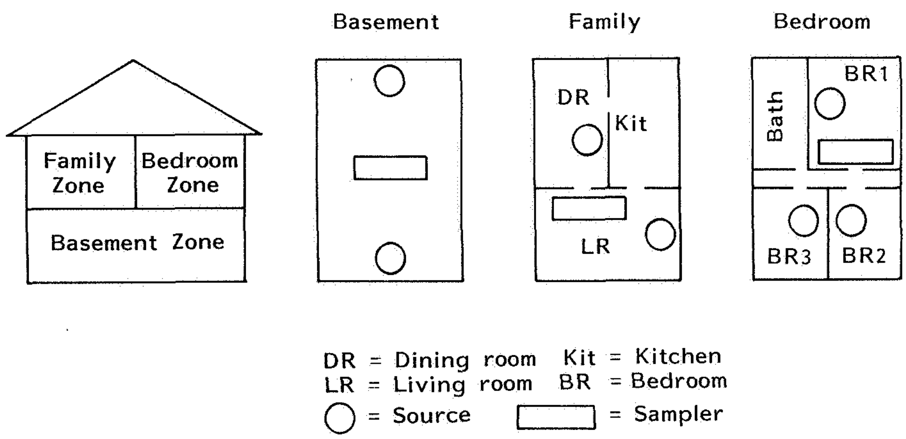

Figure 6.4.4 Source and sampler location for a one-storey house with basement

In a two storey home, two sources of one type are deployed on the main floor e.g., the living room and family or dining area) and one of a second type in each bedroom upstairs (see Figure 6.6.5). If the living area is to be treated as a single zone, then only two sources of one type should be deployed on the main floor. The stack effect will provide an essentially equal concentration upstairs without sources; the concentration should, however, be measured upstairs as well as on the main floor. During these tests, the doors to all rooms should remain open with the exception of the basement doorway which should be closed if that is its normal position.

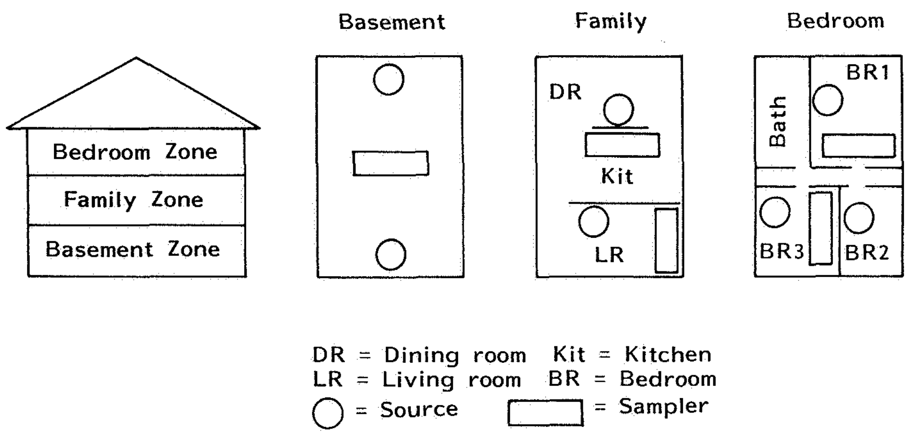

Figure 6.4.5 Source and sampler location for a two storey house with basement

The sources are used as received; they are always emitting tracer, there is nothing to open or uncover, and they may be placed in any orientation. Generally, a PFT source is placed within 0.5 to 1.5 metres of the floor and no closer than 1 m to an outside wall. For example, it can be taped to the leg of a table or even on a lower portion of a hanging chandelier. Since the source is sensitive to temperature, it should not be placed within a metre of a heating or cooling source, in direct sunlight or other draughty location such as a window, nor at a location where air would carry the PFT vapours outside or to another zone before they had mixed uniformly within the zone where they were placed. Since heated air rises and cooled air sinks, the PFT source should be at a vertical location not too far above or below the temperature measurement/control elevation, and should not be placed above a warm air source (e.g., a lamp or the top of a refrigerator) nor below a cooled air source (e.g., an air conditioner vent or a window sill). The average temperature of the source must be recorded. Note: the daily average room temperature is usually adequate for this purpose, even in the case of one or more daily temperature set-back cycles.

The choice of PFT source types with zone location is important in multizone structures. Because of the stack effect in all houses, a source placed on the second floor will have a very low concentration in the basement. To improve the precision of its measurement in the basement, the second floor tracer selected should be one with the highest emission rate and the highest detectability, i.e., the earliest eluting tracer on the gas chromatograph (GC) column. Thus the choice for the second floor tracer in a 3-zone study is either PDCB or PMCP (see Table 6.4.1). The same reasoning extended to the other floors dictates that PMCH be used on the first floor and PDCH in the basement. The use of PDCB in one zone and PMCH in another zone in a 3-zone building should be avoided because those two tracers elute very close to each other and are therefore difficult to quantify without using special GC conditions. In stacked 4-zone structures, when both PDCB and PMCP must be used, the correct choice for the uppermost zone is PDCB, followed by PMCP in the next lower zone, PMCH in the next, and PDCH in the lowest zone.

Samplers

The passive samplers are also shipped under separate cover: under no circumstances should the sources and samplers be stored at the same location. The sources and samplers should definitely not be shipped in the same container and, ideally, not even shipped on the same day. For example, if transported in the same car or truck, there is a possibility of contamination. During field deployment, the samplers can be placed in the engine compartment of a vehicle (effectively outside) while the sources are maintained within the vehicle passenger compartment or truck. To this end it is usual for one or two passive samplers to remain as controls, that is, to remain unopened, for each series of home infiltration measurements.

One or two samplers are usually deployed in each zone of the home with the same location restrictions as the sources and at least 1 to 2 metres from any PFT source or source of air not representative of the room air (e.g., air from outside or another zone). Thus, the samplers are usually placed near another inside wall location (but at least 2 cm from any wall), and not in a flowing air stream without a shelter (such as an envelope or box). In the bedroom zone of a house, it is prudent to sample in the master bedroom plus one other bedroom; this provides a better average for that zone. The samplers are not temperature sensitive, but extremes should be avoided. They can be placed on a table or taped to the leg of a chair or table in any orientation.

Stabilising period

There is no stabilising period required once the sources are in the measurement building. Usually sources are fabricated then set aside for a period of time to allow them to achieve a steady rate of emission. The PFT sources are ready for use about 12 days after manufacture.

Sample Rate

The sampling rate is proportional to the tracer diffusivity in air; the theoretical effective air sampling rates for each tracer are:

PDCB)
PMCP) 214 mL/day

PMCH 201 mL/day

PDCH 188 mL/day

Measurement Duration

To initiate sampling, the rubber cap near the numbered end is removed from the end of the sampling tube. The sampler number, location, and the time and date sampling commenced must be recorded. At the end of the designated measurement period (for example - 1 day, 1 week, 1 month), the sampler is capped and a record made of the time and date sampling ceased. If it is required to compute air changes for the house, then the volume of each zone should be recorded.

6.4.5 PRESENTATION OF RESULTS

If the building is considered to be a single well mixed zone, then the average air infiltration rate of the whole building is presented in air changes per hour. In the multi-zone case, air infiltration and exfiltration rates from each zone, as well as the air exchange rates between zones, are presented along with the standard error estimate for each flow. Figure 6.4.6 gives an example of evaluated three-zone flow rates. When the two living areas are combined and treated as one, it was shown that the errors on the remaining two-zone flows were much smaller than the initial case. Flow rates are reported in cubic metres (measured at 25 °C and 1 atm.) per hour.

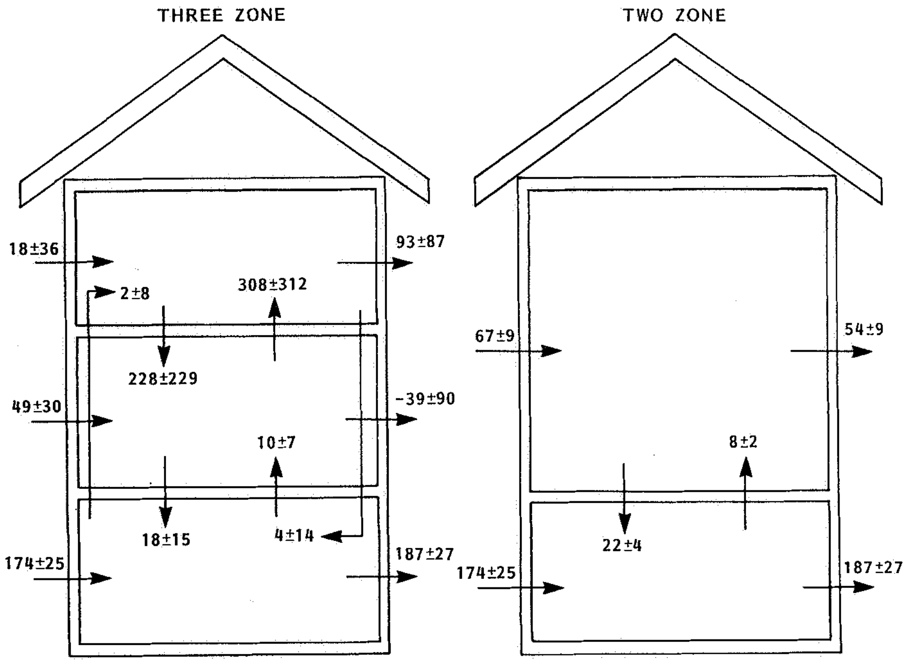

Figure 6.4.6 Presentation of air flow measurement results (flow rates in m^3h^{-1})

6.4.6 MEASUREMENT ACCURACY

The passive monitoring system has been tested against an automated sulphur hexafluoride decay system that measured the infiltration rate every 90 minutes. Measurements were made in a dwelling over a period of about 20 days. Using PDCH, the average air infiltration rate was computed to be 0.31 air changes per hour. This was in good agreement with the 0.33 air changes per hour value obtained from the average of the sulphur hexafluoride decay measurements. Several other intercomparisons in both field and laboratory trials have shown the PFT measurement accuracy to be about ± 10% in the absence of large occupancy and ventilation variations (e.g., see Leaderer et al [1985]).

The accuracy of the field measurements is about 10-15%. The main factors affecting the accuracy are:

Temperature: The sources are permeation devices calibrated at 25 °C.

A 1 °C increase in temperature increases the tracer gas emission rate by 4%.

Analytical: Analytical accuracy is within ± 5%

Air mixing: As in any tracer method, departure from the assumption that the zone air is well mixed will introduce errors.

The errors associated with passive ventilation measurements were examined by Sherman [1987]. This study relied on mathematical models combined with typical weather data to calculate how an ideal passive ventilation measurement would perform. It was found that the passive technique tended to under predict the average ventilation rate (this is known as "negative bias"), and that to decrease this effect multiple injectors and samplers should be used. Sherman states that this technique is appropriate for indoor air quality measurements. The effective ventilation measured by the passive technique can be used directly to estimate the average concentration of any pollutant of (known) constant source strength.

Model calculations by D'Ottavio et al [1988] confirmed experimental measurements which showed that weather induced variations in building air infiltration caused biases of 3-5% in winter periods and 12-17% in summer periods. For moderately large variations in ventilation rate after short periods, such as caused by opening a window for 1-3 hours, the bias in determining the average ventilation rate is less than 25%. The rate determined by this method more closely reflects the performance of the building without occupancy effects.

COMMENTS

A good companion for the passive tracer system would be a passive temperature sensor. This would allow the emission rate to be more accurately determined. Temperature controllers could be used to maintain the PFT source at a constant temperature and stabilise emission rate. However, the source would require 12 days to stabilise, and the effective cost of the tracer sources would increase significantly.

6.4.8 AVAILABILITY OF MEASUREMENT SYSTEM

The tracer gas emitters and the passive sampling tubes are relatively inexpensive and designed to be used by home owners after they have received them through the mail. The laboratory based equipment is expensive although one facility could handle the analysis of many passive samplers.

Further information about this technique as described here can be obtained from:

Dr Russel N Dietz, Head
Tracer Technology Centre
Brookhaven National Laboratory
Associated Universities Inc
Upton
Long Island
New York 11973
USA

Tel: 516 282 3059

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6.5.1 TYPE OF TECHNIQUE

TRACER GAS CONSTANT CONCENTRATION

Parameter(s) Evaluated

Automatic registration of the fresh air exchange rate in several separate zones of an occupied building.

Measurement Principle

A constant concentration of tracer gas is maintained within each measured zone. The tracer gas injection rate required to maintain this concentration is monitored. The fresh air exchange rate is directly proportional to the tracer gas injection rate. The basic principles of this method are presented in Section 2.1.3.

6.5.2 RANGE OF APPLICATION

This technique has been used extensively to examine air infiltration rates in dwellings. In particular it has proved very useful in the study of the influence of building occupants on air infiltration rates.

This measurement technique has also been used successfully in commercial, industrial and public buildings. Examples of the use of this technique are given by Collet and Egedorf [1988].

6.5.3 EQUIPMENT AND INSTRUMENTATION

The constant concentration technique requires sophisticated control and analysis instrumentation. One such instrument package is described here.

General Description

The air change measuring equipment consists of:

1 x microcomputer
1 x gas analyser
2 x specially constructed control boxes
1 x cylinder of tracer gas (sulphur hexafluoride)
1 x cylinder of calibration gas

The component items are stacked together to form a trolley (see Figure 6.5.1), thus enabling the equipment to be easily moved within the measurement building.

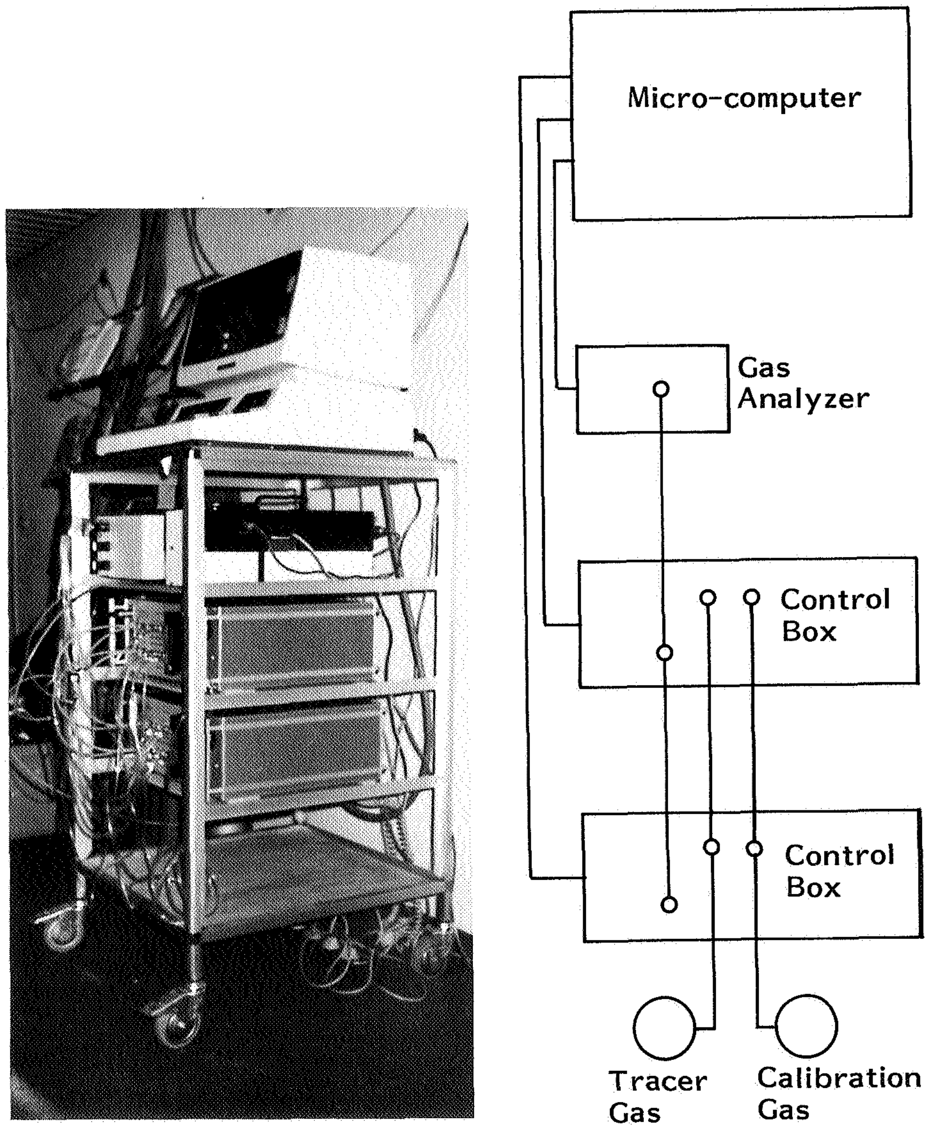

Figure 6.5.1 **Photograph and schematic of constant concentration device**

<u>Microcomputer</u>

<u>Hardware</u>

The microcomputer is used to control the operation of the air change measurement equipment. In order to do this, the computer is fitted with a board for analog input and digital output. The microcomputer is also used for the evaluation and storage of air change rate data. Data are stored on standard diskettes, each of which can store data from up to eight days continuous measuring.

Software

The computer software is used for the control of the tracer gas injection valves and air sampling valves. It also enables measured values to be read and data to be stored on diskette. A specially written programme contains an algorithm for calculating the required amount of tracer gas which has to be injected to maintain a constant concentration of tracer gas within the measurement zones. A PID type (Proportional Integral Derivative) adjustment algorithm is used. Bohac [1986] discusses the use of this and other types of algorithm for controlling constant concentration in tracer gas equipment. Calculations are carried out on the basis of the monitored tracer gas concentrations.

Gas Analyser

The tracer gas concentration is monitored by a single beam infra-red gas absorption analyser. This detector makes use of the infra-red absorbing properties of the tracer gas. Infra-red absorption analysers are described in Section 4.2 and details of a specific analyser are presented in Section 7.2.

In the infra-red gas analyser, variable infra-red filters are utilised. These can be set at any wave length within their range, thus allowing a variety of gases to be analysed by the single instrument. In this case the filter is set to detect sulphur hexafluoride. The amount of infra-red absorption measured is determined and converted to parts-per-million (ppm) for a direct meter read-out. Sulphur hexafluoride has a minimum detectable concentration level of 0.02 ppm. The use of the detector's recorder output jacks enables the gas concentration signal to be fed into the analog input board of the computer.

Control Boxes

The two identical control boxes each have two functions:

(i) To regulate the injection rate of tracer gas.
(ii) To sample the air for analysis.

Injection Control

In order to maintain a constant concentration, controllable volumes of tracer gas must be injected into the measurement zones. This is performed by a unit which consists of five solenoid dosage valves (per control box) and a pressure transducer for reading the level of tracer gas pressure (see Figure 6.5.2).

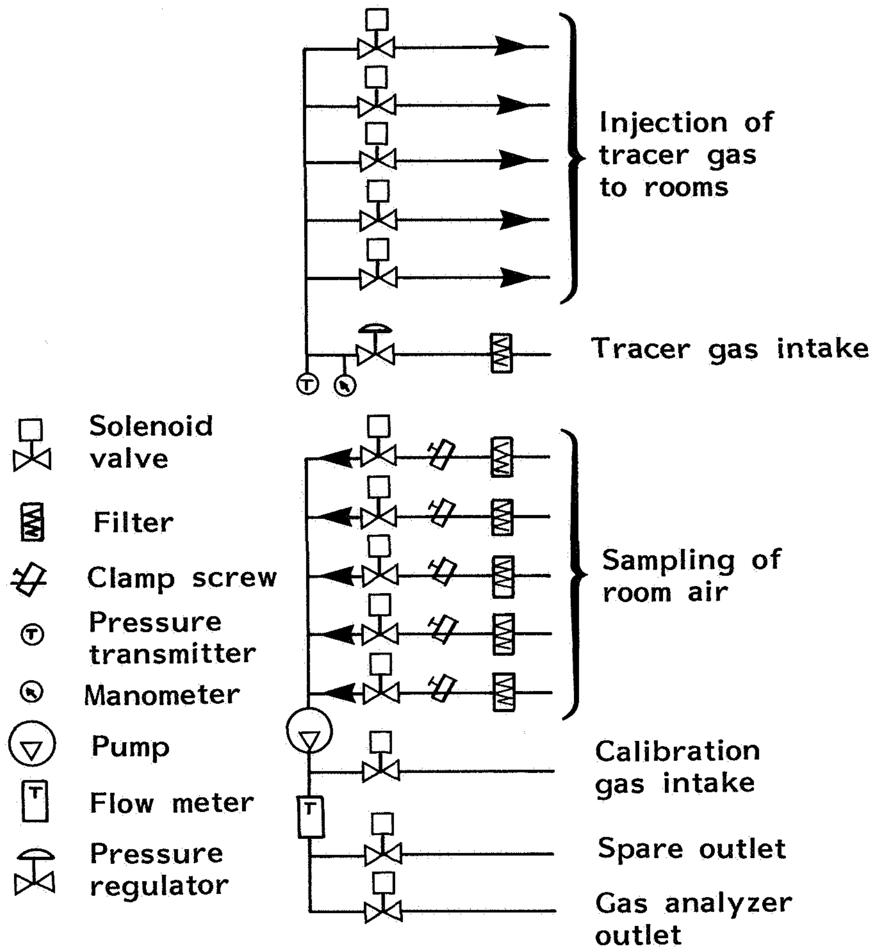

Figure 6.5.2 Schematic of constant concentration device control boxes

The injection of tracer gas is regulated by opening the solenoid valves for a selected time interval. This operation is controlled by the microcomputer.

A simple method is used for the accurate calculation and control of the tracer gas flow through the valves. Each valve has a injection nozzle. The nozzle and the excess pressure of the tracer gas are selected so as to create an over-critical flow in the narrowest cross-section of the nozzle.

An over-critical flow is produced when, in this case, the ratio of the upstream pressure to the downstream pressure is greater than 1.9. At this over-critical flow, the tracer gas reaches the local velocity of sound and cannot be further increased by increasing the upstream pressure. When the volume flow is constant, the total mass flow is dependent only on the density of the gas.

Under these conditions the mass flow of tracer gas is given by:

$$M = Cn \frac{P}{\sqrt{T}} \qquad [6.5.1]$$

Where

M = Mass flow of tracer gas in nozzle, kg s^{-1}

Cn = Nozzle constant

P = Upstream pressure of gas, Pa

T = Temperature of gas at upstream side of nozzle, k

Hence the mass flow in this case is dependent only upon the upstream pressure and temperature. Therefore, from a knowledge of the nozzle characteristics and the tracer gas pressure, the mass flow per unit time can be evaluated. The amount of tracer gas injected into a zone can be controlled by opening the relevant injection valve for a given period of time. These valves also have highly quadratic characteristics, i.e. five 2-second injections provide the same amount of gas as one 10-second injection.

Sample Control

Each control box also has an air sampling unit (see Figure 6.5.2). This consists of five solenoid sample valves, and these are similar to the injection valves described above. The computer controls the opening and closing of the valves depending on the point at which the air is to be sampled. The computer identifies the zone from which the air is being drawn. At a maximum interval of ten minutes the gas concentration of each zone is evaluated.

The sample air is drawn through the system by means of an adjustable flow pump. Before being analysed, the air passes through a dust filter. The outlet for the sample air to the gas analyser and the inlet for the calibration gas to the gas analyser are also part of the sampling unit.

Gases

The tracer gas and calibration gas are kept in 5-litre cylinders and these are linked to the control boxes via a pressure regulator. The tracer gas used is sulphur hexafluoride.

A neutral gas, nitrogen, and a mixture gas are used as calibration gases. The mixture gas consists of tracer gas in neutral gas in a proportion corresponding to the desired concentration in the rooms (10 ppm). These gases are used for the calibration of the gas analyser and for its periodic control.

6.5.4 SETTING UP AND OPERATING DETAILS

The building is initially prepared so as to correspond to the desired measurement situation.

General Setup Details

The air change measurement unit is placed at a central location within the building. It is desirable to site equipment in a position which causes minimal disturbance to occupants. Two plastic tubes, 1 x 3 mm dia for gas injection and 1 x 4 mm dia for air sampling, are led from each zone selected for measurement to the control boxes. The tubes are connected to the injection and sampling valves on the control boxes.

Tubes with a small diameter have the advantage of enabling the zone air to be sampled more rapidly and pose fewer problems at lead-ins. Tubes can be led through doors, via keyholes, drilled holes or possibly through the gap between door and floor, the criterion being that the door must still be usable in the normal manner. An example of one method is shown in Figure 6.5.3. To avoid long lengths of tube trailing on the floor, they can be taped to the ceiling or, if convenient, led through service ductwork. Here the criterion is the avoidance of long-term disturbance to building occupants. These methods are ideal for any technique which requires long lengths of tubing to be led through a building.

A small mixing fan is placed at each injection point. The purpose of the fan is to blend the tracer gas with the room air. The gas is then further mixed due to the natural air circulation of the room.

Special perforated injection tubes with closed ends can be used in bedrooms, bathrooms or other situations where it is desirable to avoid noise or live leads in wet rooms. The time required to set up the air change measurement system will vary from building to building and on the number of sample zones to be evaluated. However, an approximate guideline time would be around three hours for one experienced operator.

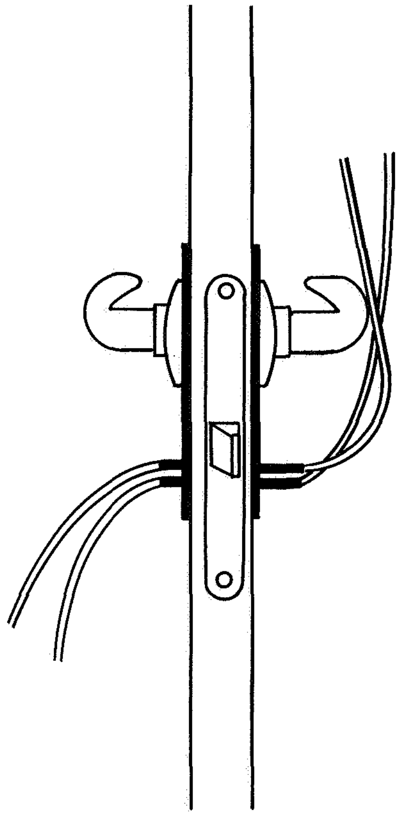

Figure 6.5.3 One means of leading sample or injection tubes through a door

Position of Sample Points

The injection and sample points are placed at the same height in each zone (approximately at the midpoint between floor and ceiling) and as far away from each other as possible (see Figure 6.5.4). If there is a mechanical ventilation system in operation in the building, then the injection points should be placed near the air inlets. Injection and sampling points must not be placed too close to external doors or windows which can be opened.

Care must also be taken to ensure that the injection points are placed so as not to affect the sampling points before the tracer gas has adequately mixed with the room air. It is also important that the location of injection points does not affect measurements in other rooms. An initial indication of the air flow can be determined using smoke visualisation.

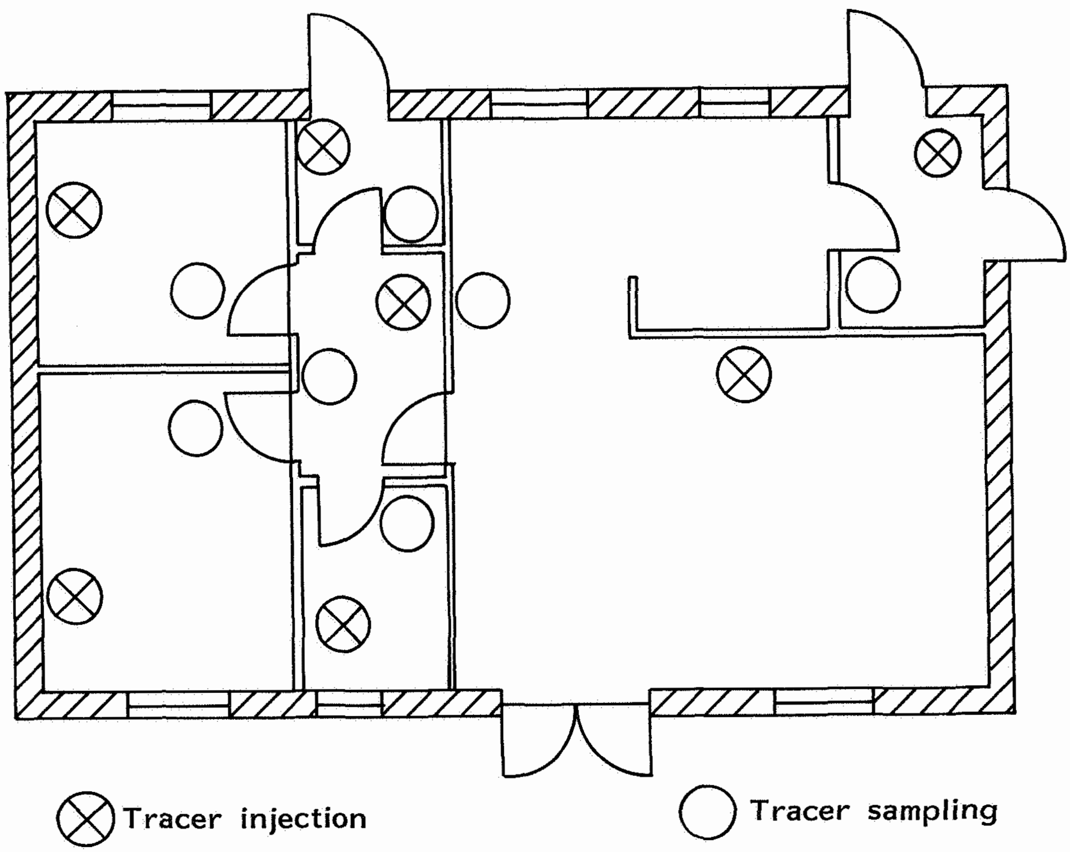

Figure 6.5.4 Example of correct location of injection and sampling points for constant concentration method

Stabilising Period

Once the air change measurement system has been set up it is run for two hours to allow the concentration of tracer gas to stabilise at the target value (usually 5-10 ppm). The tracer gas concentration is then measured in different parts of the measured zones. If the variation in gas concentration prevents the desired degree of accuracy in the results, the location of the injection and sampling points must be adjusted accordingly.

Sample Rates

The system is configured so that the tracer gas concentration at each sampling point is registered once every 10 minutes. The zones are injected with tracer gas every 40th record. The injection time can be varied from 0 to 30 seconds with a minimum injection time of 2 seconds. The valves used have precise quadratic characteristics.

Thus five 2-second doses provide the same volume of gas as one 10-second dose.

Measurement Duration

Once the system is fully operational it can run for up to 8 days continuously. After this time the floppy disk on which the data are stored requires replacement. The replacement of tracer and calibration gas supplies will also periodically interrupt operations.

6.5.5 PRESENTATION OF RESULTS

The air change rate measurements are recorded as a curve where the x-axis indicates the time in hours and days, and the y-axis indicates the air change rate. This type of presentation has already been illustrated in Figure 2.3.2. Figure 2.3.2 shows just one curve; however a family of curves could be shown on the same graph. These would indicate the air change rates of the individual measurement zones. Wind velocity, outdoor temperature and wind direction are given under the x-axis.

6.5.6 MEASUREMENT ACCURACY

The accuracy of the air infiltration measurements is calculated according to the error accumulation law. In this system there are several sources of error:

Inaccuracy of supply of tracer gas error

Approximately ± 2%.

Inaccuracy of evaluation of tracer gas concentration

Calibration gas error approximately ± 1%.
Infra-red analyser error approximately ± 3%.

Inaccuracy due to uneven tracer gas concentration in measured zone

Inaccuracy due to variation at single point. Inaccuracy due to concentration differences between different points in a zone and also from zone-to-zone.

Total measurement error

In the case of measuring areas with a constant air infiltration rate, the total measuring inaccuracy does not exceed ± 5% when average values over a period of two hours are taken.

In the case of measuring areas with varying air infiltration rates, the measurement inaccuracy does not exceed 10% when average values are taken over a period of one hour.

A general discussion on constant concentration method measurement errors is presented by Bohac [1986].

6.5.7 COMMENTS

Weather Parameters

During the measurement of air change rates, the parameters influencing air infiltration are recorded, e.g. the setting of the mechanical ventilation system, opened or closed vent holes and windows. Wind direction, wind speed and outdoor temperature statistics for the measurement period are obtained from local meteorological stations.

Extensions to Measurement Device

Units for the continuous measurement of humidity, temperature or carbon dioxide levels can be added to the air change measurement equipment. These data are also stored by the microcomputer on floppy disks.

A standard relating to this technique has been developed; this standard is described in more detail in Section 5.1.1.

6.5.8 AVAILABILITY OF MEASUREMENT SYSTEM

This constant concentration air change measurement system is available as a complete package from the contact given below. Several units have been supplied to research institutes. For further information, contact:

Peter Collet
Technological Institute
Byggeteknik
Post Box 141
Gregersensvej
DK 2630 Tastrup
Denmark

Tel: 02 996611

Several other organisations have experience of the development and production of constant concentration equipment packages. A selection is presented below.

David Bohac
Centre for Energy and Environmental Studies
Princeton University
Princeton
New Jersey 08544
USA

Tel: 609 452 5190

Claude-Alain Roulet
Laboratoire d'Energie Solaire et de Physique du Batiment
Federal Institute of Technology
LESO-EPFL
CH-1015 Lausanne
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Tel: Int +41 21 474 557

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Collet, P.F. and Egedorf, M. [1988].
Ten Years of Constant Concentration Tracer Gas Measurements.
Air Infiltration Review, Vol 9, No 2, pp2-3, February 1988.

6.6.1 TYPE OF TECHNIQUE

MULTIPLE TRACER GAS DECAY RATE

Parameter(s) Measured

Measurement of air flow rates between internal spaces of compartmentalised buildings.

Measurement Principle

If two-directional air movement exists between two connected spaces where a tracer gas has been released, recirculation of tracer gas will occur. Consequently the shape of the tracer decay curve in the source room will not be a simple exponential function. Generally, however, the slope of the tracer curve approximates to a single exponential during the first 10-15 minutes after tracer release. Provided a sufficient number of concentration and time points are available, i.e. at least ten, then a good estimate of the source room air change rate can be obtained using "first order" estimates. These estimates can then be used to evaluate true air change rates and interzonal air flows.

In this technique tracer gases are released, one to each cell, and the concentration of all gases in all cells is monitored over a 15-20 minute period. The system enables data points to be taken in rapid succession thus allowing concentration and time values to be analysed and interzonal air flows to be evaluated.

6.6.2 RANGE OF APPLICATION

This technique has been used to examine air movement in dwellings. Successful measurements have been made by dividing the dwelling into up to three separate zones, e.g. kitchen, bathroom and the rest of the house. This technique has proved particularly useful in the assessment of potential condensation problems due to moisture migration, and specific projects have included the examination of the effectiveness of roof ventilators and more complex passive ventilation systems.

6.6.3 EQUIPMENT AND INSTRUMENTATION

This section contains a description of one instrument package designed to perform rapid measurements of interzonal air flows.

General Description

Tracer gas concentrations are evaluated using a rapid response double column gas chromatograph with an electron capture detector. A schematic diagram of this equipment is shown in Figure 6.6.1. The system is an adaptation of a commercially available leak detector, originally supplied with a single gas separation column. This is replaced with twin columns and switching between these enables samples to be taken in rapid succession. The whole system is portable and manually operated.

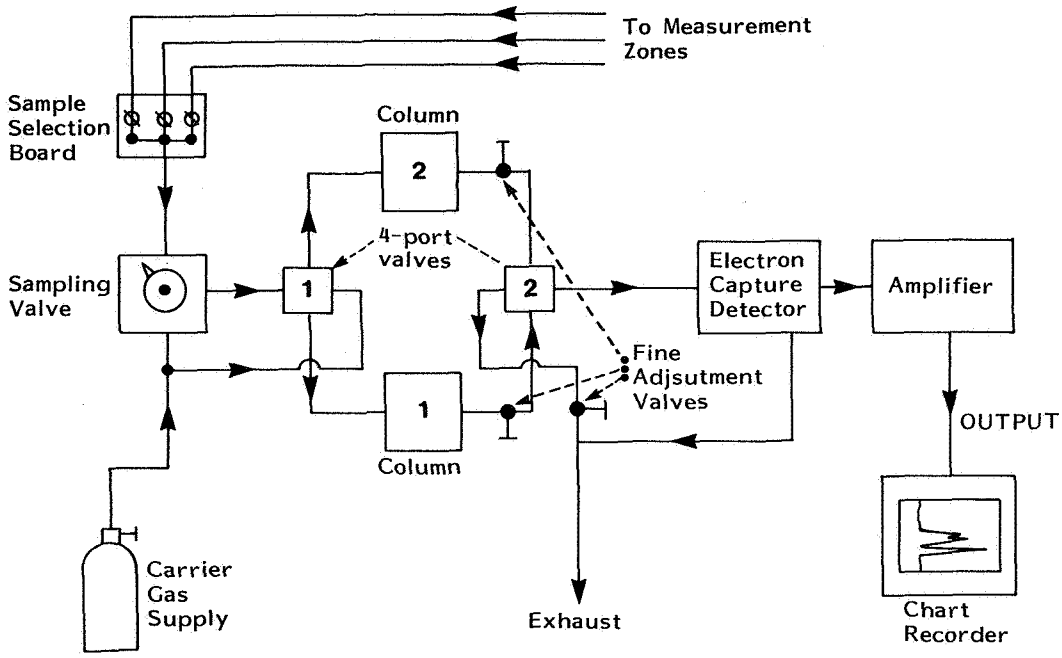


Figure 6.6.1 Schematic of two column rapid response tracer gas system

Zone Selection Board

This simple arrangement of three on/off valves allows air samples to be taken from individual zones. The suction power is provided by a small pump which continually draws air through the sample line.

Sample Valve

The manually operated six-port sample valve isolates a fixed volume (0.5cc) of the air tracer mixture from the sample line. The sample is then carried towards the columns by the argon carrier gas which is supplied from a small cylinder, at a pressure of 3 bar.

Chromatograph Columns

Air samples are carried through the columns by the argon carrier gas. The role of the columns is to separate the tracer gases and atmospheric oxygen before the air sample reaches the detector cell. Each gas is absorbed and desorbed at different rates by the material in the column, causing the component gases to arrive at the downstream end of the column at different times.

Column Specifications

material	:	stainless steel
length	:	3 m (coiled to approx. 8 cm diameter)
diameter	:	6 mm
packing	:	10% squalane
support	:	90% C.N.A.W. diatomaceous earth (inert packing material)

The columns are used alternately for consecutive samples. Thus a faster sampling time is achieved by virtue of the fact that the "dead time" associated with waiting for a sample to pass through a single column is eliminated. In order to ensure that the columns respond in an identical manner, the following three conditions are adopted as standard.

1. Columns are bought from the same manufacturer and packed during the same production run from the same batch of packing material.
   One column manufacturer is given in Section 6.6.8.

2. Before use, both columns must be baked in parallel in an oven at 100 °C for 12 hours, with the purging gas (argon) being drawn from the same cylinder.

3. When not in use, both columns are kept under a blanket of argon, with the purging gas being drawn from the same cylinder.

At room temperature, small fluctuations in temperature can have significant effects on the performance of a column. During operation, the columns are placed in a thermostatically controlled water bath capable of holding the water temperature to ± 0.1 °C of a given temperature. The holding temperature must be above normal ambient temperatures. For two-cell (two-gas) measurements 30 °C is sufficient, and for three-cell (three-gas) measurements the water bath temperature is raised to 50 °C.

Four-Port Valves

Two dead volume valves are used in the system. Each valve has four ports and, by a single turning action, two inputs can be directed to either of two outlets (see Figure 6.6.2).

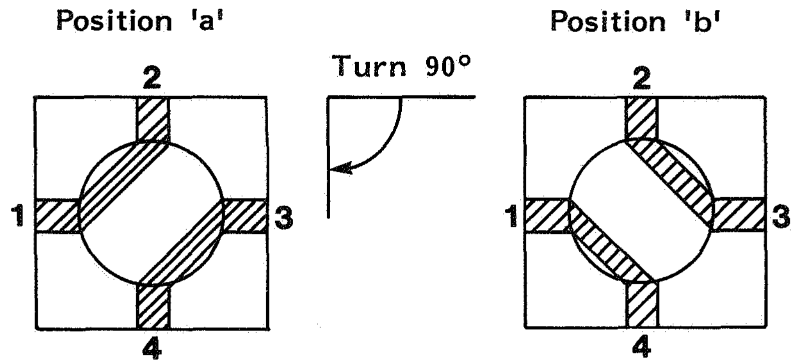


Figure 6.6.2 Four-port valves switching positions (see Table 6.6.1 and Figure 6.6.1)

Valve 1

This valve determines to which column the sample is directed, the other column being automatically kept under a trickle of Argon from the carrier gas supply cylinder. Switching the valve reverses the roles of the columns.

Valve 2

Gas streams from the two columns are the inputs to the second four-port valve. The position of this valve determines whether the stream from a column is sent to the detector cell or to exhaust.

Fine Adjustment Valves

Needle valves are located after the separation columns. These are used to adjust and equalise the pressures in both legs of the system, electron capture detector output being sensitive to operating pressure. A third needle valve is situated in the exhaust line, thus enabling its resistance to be matched to the electron capture detector.

Detector Cell

The electron capture detector comprises two oppositely charged plates and a radioactive beta particle source (10 Mc). The source causes an excess of negative ions in the detector which are collected at the positively charged plate causing a current flow (standing current). When an electron absorbing gas, such as tracer or oxygen, passes through the detector cell, it captures a quantity of electrons. The standing current decreases and this drop in current is monitored, amplified and fed into an x-t chart recorder. Decreases in standing current can be related to the concentration of detected tracer gas. Figure 6.6.3 shows the full detector output of an air sample containing three tracer gases.

Tracer Gases

The output given in Figure 6.6.3 shows three tracer gases which belong to the freon family. These are particularly suitable in that they are non-toxic, highly electron capturing and easily separable using gas chromatographic techniques. Some characteristics of these gases have already been presented in Table 4.1.1.

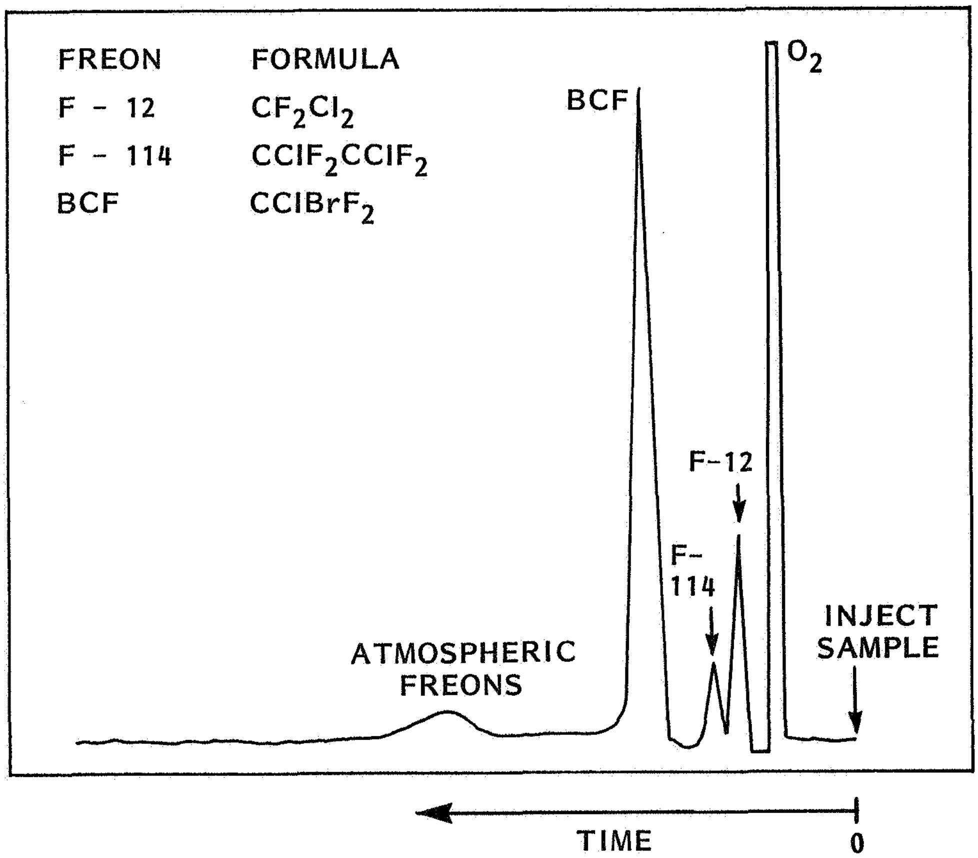


Figure 6.6.3 Full output of a single column detector

6.6.4 SETTING UP AND OPERATING DETAILS

Initial Preparation

The equipment is transported to the site and the column detection system placed in a suitable location. The heated water tank is set to the required temperature and the columns placed in it. Some time must be allowed for the system to stabilise and, during this period, the chromatographic columns are kept under a blanket of argon. Polythene sampling tubes (8 mm outside diameter) are led to the relevant locations. Each tube terminates in a "spider" from which three tubes are placed at different heights and locations in the cell under test. This sampling manifold is intended to lessen the effects of any concentration gradients which may have developed from stratification of tracer gases. When the system is ready for use, the tracer gases are released, one to each cell under consideration.

Tracer Injection

Tracer gases are introduced into a test space in one of two ways. The first is to inject the tracer gas remotely using a gastight syringe via a septum port into a polythene tube which is flushed with argon. Alternatively, tracer gas may be injected manually from the gas cylinder in the appropriate space by briefly opening the cylinder valve. The amount of gas to be released can be approximately determined from the volume of the test spaces and the detectability of the tracer (see Table 4.1.1.). After injection, the gases are mixed using oscillating desk fans (minimum two per cell). Mixing is generally found to be adequate five minutes after initial tracer injection.

Tracer Sampling

Each cell must be sampled in turn, this action being controlled by the valves on the zone selection board. Air samples are introduced into the column system using the sample valve, and the two four-port valves are used to direct the sample to the correct column, and from there to either the detector or exhaust. This complex process of valve switching must be performed to a strict schedule, thus enabling the sampling interval to be as short as possible.

Table 6.6.1 presents the switching sequence of the sample and four-port valves for a 30-second sample interval. In addition the correct zone must be selected before a sample is taken.

By using the the switching sequence given in Table 6.6.1 it is possible to obtain many concentration points in a

TABLE 6.6.1. SWITCHING SEQUENCE FOR 4-PORT VALVES

TIME (s)	ACTION	POSITION OF VALVE 1*	POSITION OF VALVE 2*	SYSTEM STATUS
0–3	Inject sample	a	b	Sample directed to column 1
12	Switch 1	b	b	Sample going through column 1: column 2 on line ready for next sample
23	Switch 2	b	a	ECD on line to column 1. Ready to receive sample
30–33	Inject sample	b	a	First sample shows an ECD output: second sample column 2
42	Switch 1	a	a	First sample still being output: second sample going through column 2: column 1 on line ready for next sample
52	Switch 2	a	b	First sample finished with: ECD on line ready to receive second sample
60–63	Inject sample	a	b	Second sample shows as ECD output: third sample directed to column 1

*Refer to Figures 6.6.1. and 6.6.2.

relatively short time. Ideally ten concentration points should be obtained for each cell during the first 15-20 minutes after injection and mixing has taken place. Figure 6.6.4 shows the output of the electron capture detector, for three consecutive samples, as recorded on the x-t chart recorder.

6.6.5 PRESENTATION OF RESULTS

Initial Analysis

It is common practice in gas chromatography to relate the area under the peaks, as shown in Figure 6.6.4, to the concentration of tracer gas being measured. However, assessment of peak areas in field measurements is time consuming. An alternative approach is to measure peak heights, which are calibrated using mixtures of known concentrations of tracer made up with inert argon. By

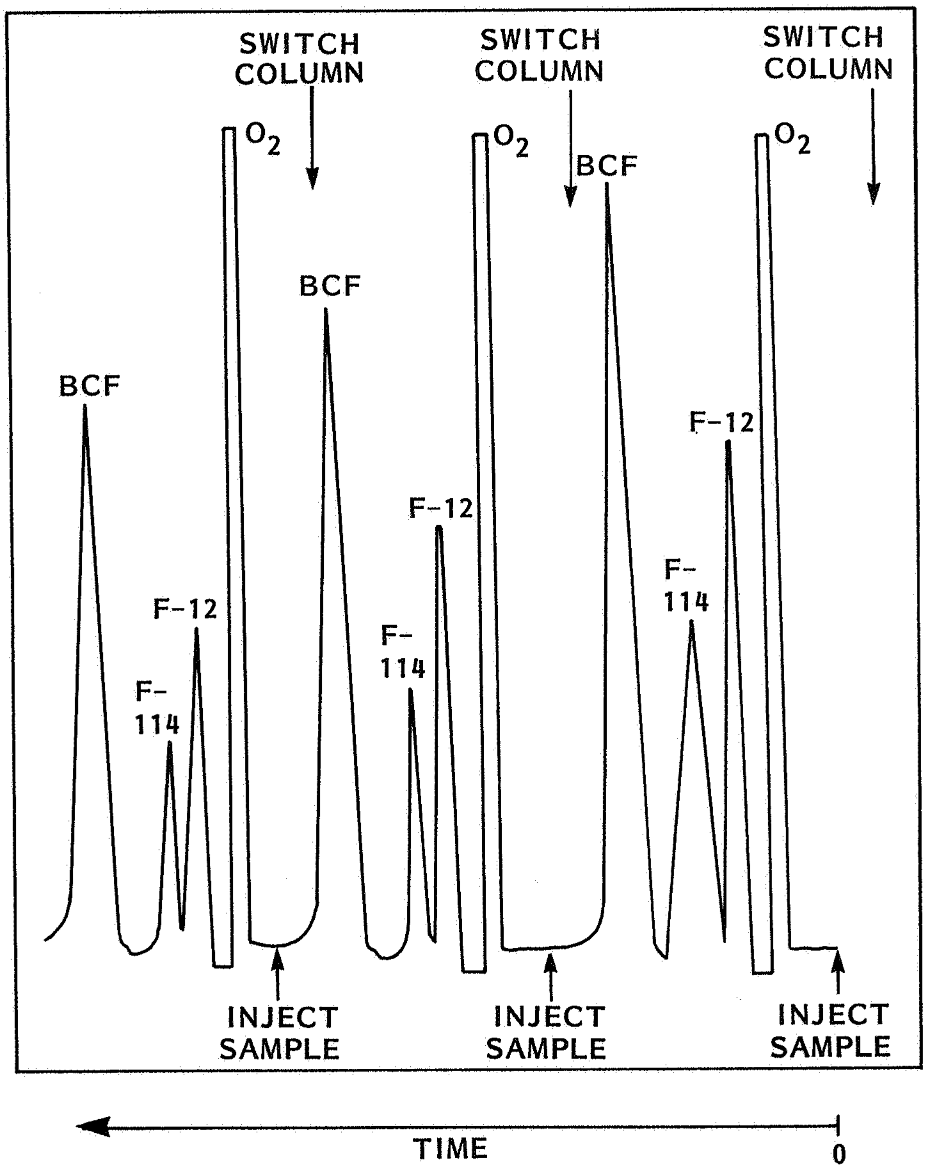


Figure 6.6.4 Output of two column system with three tracer gases showing reduction of dead time and decay of tracer

evaluating the peak heights in Figure 6.6.4, it is possible to show the time variation of tracer concentration in all measured cells.

Figure 6.6.5 shows the variation of tracer gas concentration with time for a particular case. Here, BCF was released in the cell under consideration and F-114 and F-12 were injected in adjacent cells. A 45-second sample interval was employed, thus the cell was examined every 2 minutes 25 seconds. There is a decrease in BCF concentration and an initial increase in concentration of the other two tracers. In this case, the air change rates are quite high causing rapid changes of tracer gas concentration with time, all three tracers tending towards equilibrium in 12 minutes.

This still allows enough data points to be obtained to enable the flows between cells to be calculated. The concentration data is fed into a microcomputer. Special software has been written which enables the air flow rates between cells to be calculated. A description of this analysis procedure is beyond the scope of this document. However, a full account is given by Irwin [1985].

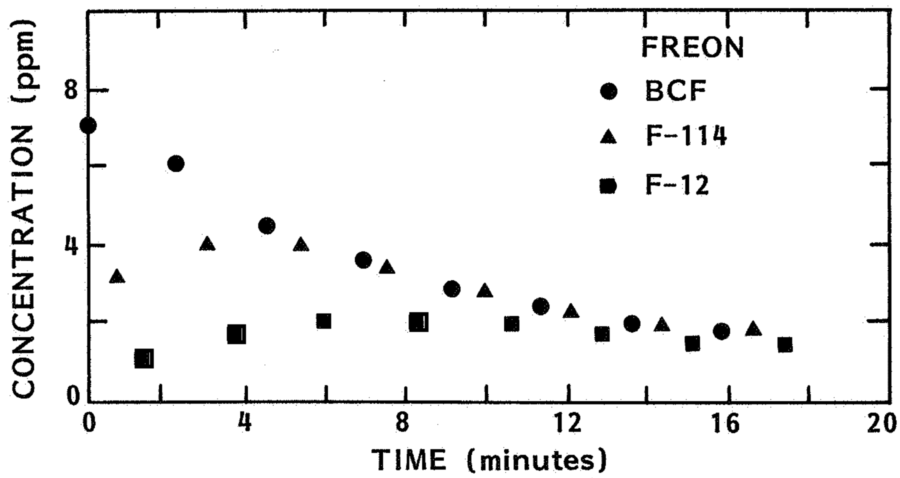


Figure 6.6.5 Plot of concentration v time for three tracer gases in a zone where BCF was realeased

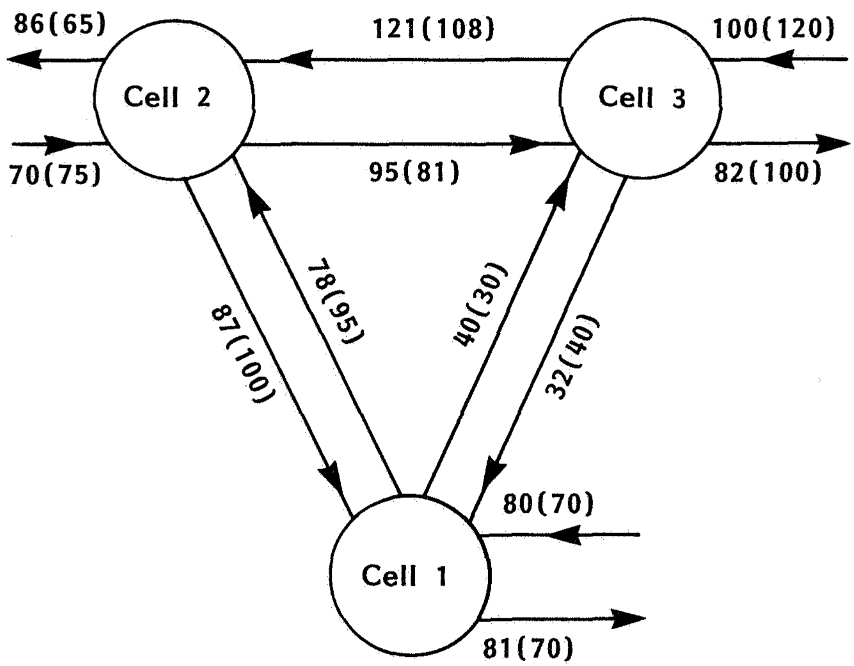
Final Presentation

Because of the complexities of the situations examined by this technique, a useful method of presenting the results is in diagrammatic form. The results of a test performed in a dwelling which examined the air flows between kitchen, bedroom and the rest of the house, have already been shown in Figure 2.3.1. The wind speed, wind direction and condition of the building are shown. These parameters will affect the value of the air change rates and interzonal air flows.

6.6.6 MEASUREMENT ACCURACY

The accuracy of this technique has been extensively examined using laboratory based environmental chambers. Initially a simple single chamber ventilation rate measurement was taken using all three tracer gases. This indicated that the difference in response between the pair of columns was in the order of 0.5%.

A three-cell environmental chamber arrangement was used to test the inter-cell flow capability. Air movements between the three cells were induced by means of ducted low speed fans in combination with the air supply system feeding the chambers. Air velocities in the supply ductwork were measured using a pitot tube and a manometer, while air velocities between cells were measured using a hot wire anemometer probe. The tracer gases were injected remotely into the cells from Cell 1 using PVC tubing. Figure 6.6.6 shows the results of one such test; the measured flow rates are in brackets. The errors between calculated air flow rates and measured air flow rates are approximately ± 20%, the effect of these errors on chamber air change rates being about ± 10%.



Air flow rates in m^3h^{-1}
(Tracer measured rates in brackets)

Figure 6.6.6 Comparison of produced and measured air flow rates between three interconnected cells

The magnitude of the inter-chamber air flows was large with respect to the chamber volumes, thus encouraging recirculation of tracer between connected chambers. Despite this, the three-cell validation work of the multiple tracer system shows that sufficiently accurate estimations of air flows can be obtained using this method over a period of about 20 minutes.

6.6.7 COMMENTS

This instrumentation has been used to examine air flow rates in buildings with up to three cells i.e. three tracer gases. A possible extension of this technique would be to automate the whole system, with control passing to the microcomputer which is used for analysing the measurements.

However, because of the complex nature of the measured air flows and the delicacy of the measurement equipment, complete automation would not necessarily be intrinsically desirable.

The apparatus described above has the ability to analyse up to three separate tracer gases. Therefore movement between three interconnected cells can be examined. A three cell capability is not adequate for all interzonal air movement studies. An extension of this apparatus has been designed which can analyse up to four interconnected cells. Two pairs of parallel gas chromatograph columns (four columns in total) are used to separate the gases, and two electron capture detectors are used to produce the concentration data. A full account of this equipment is given by Edwards and Irwin [1987].

6.6.8 AVAILABILITY OF MEASUREMENT SYSTEM

The rapid response tracer system is not available as a complete unit. However, the main component parts can be obtained from the following sources:

A.I.505 Electron Capture Detector

Analytical Instruments Ltd
London Road
Pampisford
Cambridge
Cambs.
CB2 4EF
United Kingdom

Section 7.1 presents further details of this instrument.

Gas Chromatograph Columns

J.J. (Chromatography) Ltd
Simon Scotland Road
Hardwick Industrial Estate
Kings Lynn
Norfolk
PE30 4JG
United Kingdom

For details about the assembly of the system and other information, please contact:

R. Edwards
Department of Building
University of Manchester Institute of Science & Technology (UMIST)
Sackville Street
Manchester
M60 1QD
United Kingdom

Other practical approaches to the multi-tracer decay technique have been developed. One well documented method, (See Prior [1985]), has been developed by

Josephine Prior
Building Research Establishment
Garston
Watford
Herts
WD2 7JR
United Kingdom
Tel: Int +44 923 894040

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In Text

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The measurement of air movement between four interconnected cells by a multiple tracer gas decay technique.
Roomvent 87, proceedings, Stockholm, June 1987.

Prior, J.J. [1985].
A new multi-tracer gas technique for measuring interzonal air flows in buildings.
PhD Thesis, Polytechnic of Central London, UK, 1985.

6.7.1 TYPE OF TECHNIQUE

DC PRESSURIZATION - EXTERNAL FAN

Parameter(s) Evaluated

This technique is used to evaluate various aspects of the air leakage of the building envelope at induced pressure differences.

Measurement Principles

A fan mounted in a duct which pierces the building envelope is used to create either excess overpressure or excess underpressure inside the building. This causes air to leave or enter the building via the cracks and interstices in the building envelope. The volume flow of air entering or leaving in such a manner is equivalent to that displaced by the fan. By measuring the flow rate required to create a range of pressure differentials the air leakage characteristics of the building envelope can be determined.

6.7.2 RANGE OF APPLICATION

This technique has been applied mainly in dwellings often using commercially available equipment. (See Section 4.3 for a full account of this type of equipment). Larger buildings can be examined, providing a fan system which can displace an appropriate volume of air is available.

This technique is used for a variety of applications. These include the before and after testing of retrofit measures, the evaluation of envelope permeability, leakage area and leakage distribution and the assessment of airtightness standards. Standards relating to this type of technique are discussed in Section 5.2.

This technique is designed to evaluate the air leakage characteristics of a building away from the natural influences of the climate. Therefore it is preferable to conduct the measurements when the wind speed and indoor/outdoor temperature difference are at a minimum. Otherwise these climatic parameters may introduce unnecessary errors into the results. In extreme cases they may make it impossible to take stable readings of the flow rate and pressure differential.

6.7.3 EQUIPMENT AND INSTRUMENTATION

The equipment can be divided into four basic components. These components are discussed below.

Variable Flow Rate Fan

The fan causes air to flow into (pressurization) or out of (depressurization) the building under test. It must be possible to create a range of flow rates through the fan thus enabling a variety of pressure differentials to be created across the building envelope. If large buildings are to be tested it may be necessary to use several fans in unison.

Door Panel

This panel enables the fan to be held in place in an existing aperture in the building envelope. In most practical cases the aperture used is a door frame. Essentially two types of panel exist. One made from solid panels, the other made from a flexible sheet (See Section 4.3 for more information about this subject). The main prerequisite for any panel system is that it must be able to fill and seal off the aperture into which it is placed whilst holding the fan firmly in position.

Flow Measurement

For this measurement method it is essential that two parameters be accurately evaluated, the first being the flow rate through the fan duct. Several techniques can be used to make this measurement. These are discussed in more detail in Section 4.3 and the required accuracy for the measurement of this parameter is examined in Section 6.7.6.

Pressure Differential Measurement

The importance of this technique is that it enables the flow rate through all the cracks in a building envelope to be related to the pressure differential created across the building shell. In order for the results of the measurement to characterize the building fabric itself, pressures must be created which are in excess of those produced by the natural forces of wind and temperature.

Thus any instrument used for this purpose must be able to measure differential pressures approximately in the range 0-100 Pa. One such instrument is described in Section 7.3. The pressure differential is obtained by making pressure taps on the interior and exterior of the building envelope. A single pair of pressure tappings can be sufficient. However at least one standard relating to this type of measurement demands that the exterior pressure measurement be the average of four points around the building shell, thus allowing an average pressure differential to be obtained. (See Section 5.2.1).

6.7.4 SETTING UP AND OPERATING DETAILS

Because of the variety of applications to which this technique is put, there is no unique setting up procedure for this method. Several countries have standards relating to this type of measurement, and these are examined in Section 5.2. There are several commercially available "blower doors" on the market and these each come with their own set of instructions. (See Section 4.3). Manufacturers' directions should be followed carefully and completely when conducting a test. Several general points can be made:

Preparing the Building and Setting up the Equipment

The building should be first configured to meet the needs of the current measurement. In practice this means setting windows, vents and other apertures to the position desired by the measurement. As the aim of the technique is to produce a uniform pressure difference across all parts of the envelope, then internal doors are generally left open. If the results are required in terms of air change rate, then the internal volume of the building must be evaluated. Several country standards give guidance as to how this volume should be evaluated and in general it can be calculated either from site measurements, using a tape measure, or from scale drawings using a ruler and conversion factor.

Once these preliminary setting up details have been performed the door panel and fan can be fitted into the door frame. Care must then be taken to ensure that the panel system is secure and well sealed. Internal and external pressure taps must be made and in several commercial blower doors an external pressure tap is located in the door panel itself. A more sophisticated approach involves leading tubes to all four external faces of a building and bringing them back to a small airtight vessel. One tube leads off from the vessel to the pressure differential instrument. The vessel essentially averages the pressures at the four faces of the envelope. This is particularly useful when the building is completely detached and the test is being conducted under variable wind conditions.

Another important decision to make is whether to pressurize or depressurize the building. Some standards demand that both modes be performed and average results taken. The fan must then be set up to the required flow direction to be produced. The choice of location for instrumentation such as the flow rate meter and pressure differential measurement device is, in many ways arbitrary, though in cold climates the desirability of placing the equipment on the inside of the structure is obvious.

Taking the Readings

Once the equipment is installed it is usual to take several pairs of readings of air flow rate and pressure differential. A range of pressure differentials should be examined, and several standards quote the pressure range to be used. A useful rule of thumb guide is to examine pressures in the range 0-60 Pa if this is achievable. The readings can be registered by hand or, as is quite often the case in commercial blower doors, recorded automatically by some device such as a microcomputer. If both pressurization and depressurization are required, then the fan flow must be reversed and the aforementioned process repeated.

Measurement Duration

In small domestic buildings using a commercial blower door the measurements may take as little as one hour to complete. In larger buildings where more equipment and preparation is required the measurement process may take longer.

6.7.5 PRESENTATION OF RESULTS

Several means of presenting pressurization test results have been given in Section 3.3. A full account of the advised method of presenting airtightness measurement results is given by Allen [1981].

6.7.6 MEASUREMENT ACCURACY

Two parameters are evaluated in this technique: air flow rate and pressure difference. If the results are expressed in terms of the air change rate, then the volume of the building must be evaluated. If other expressions of the results are made, then parameters such as the building envelope area must be evaluated.

An examination of the standards relating to the performance of this type of technique indicate that the following accuracy is desirable.

Flow Rate	± 5%
Pressure Difference	± 2 Pa

The measurement of building volume should also be performed with care, and although no standards of accuracies exist, it should be possible to evaluate the internal volume of a tested space to within ± 5%, especially if detailed architectural drawings are available.

One of the most important factors with regard to the accuracy of this measurement technique is wind velocity. Wind effects generate "natural" pressure differences across the building envelope. These pressure differences affect the measurement results by superimposing themselves on the pressure differences generated by the fan. The higher the wind velocity and lower the induced pressure, the greater the potential inaccuracy. It is therefore advisable to conduct pressurization tests at low wind speeds. Several standards give maximum wind speeds at which valid measurements can be made and this is discussed in Section 5.2.8.

When pressurization tests are performed, cold outside air is often blown into the building and warm internal air is discharged through the leaks. It is the flow of the cold outdoor air which is measured during the test. This must be corrected to give a value for the rate of air flow through the leaks in the building envelope. The correction equation is:

$$Q = \frac{T_i}{T_e} Q_F \qquad [6.7.1]$$

Where

Q = Air flow rate through envelope m^3s^{-1}

Q_F = Air flow rate through fan m^3s^{-1}

T_i = Internal air temperature, k

T_e = External air temperature, k

For depressurization tests the correction equation becomes.

$$Q = \frac{T_e}{T_i} Q_F \qquad [6.7.2]$$

A full discussion on fan pressurization measurement errors, calibration procedures and correction factors is presented by Kronvall [1980].

6.7.7 COMMENTS

This is a much used technique which has found applications in both research and consultancy. Apart from the simple applications described here it can be used in conjunction with other equipment to evaluate the leakage through particular building components or individual rooms (see Section 3.2).

6.7.8 AVAILABILITY OF MEASUREMENT SYSTEM

The instrumentation for performing this technique is commercially available. This type of equipment is described in more detail in Section 4.3.

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6.8.1 TYPE OF TECHNIQUE

DC PRESSURIZATION - INTERNAL FAN

Parameter(s) evaluated

This technique is used to evaluate various aspects of the air leakage of the building envelope at induced pressure differentials.

Measurement Principle

The measurement principle for this technique is very similar to the external fan pressurization method described in Section 6.7. The only major difference being that instead of an external fan the building's air-handling system is used to produce a pressure differential across the envelope. This causes air to leave or enter the building via the cracks and interstices in the building envelope. The volume flow of air entering or leaving in this manner is equivalent to the total flow through the air-handling system. By measuring the flow required to create a range of pressure differentials the air leakage characteristics of the building envelope can be determined.

6.8.2 RANGE OF APPLICATION

This technique has been mainly used in office block type buildings where the movement of large volumes of air is needed to create the required pressure differentials.

However the technique can be applied in any building where a suitable air-handling system is already installed. The criteria for suitability are that the system must be able to produce pressure differentials across the building envelope in the required range (ideally 0-60 Pa), and that it must be possible to accurately measure the total air flow rate through the system when it is in operation.

6.8.3 EQUIPMENT AND INSTRUMENTATION

The essential equipment for this technique is a suitable air-handling system, some method of evaluating the air flow through it and a means of measuring the pressure differential across the building envelope.

Air Handling System

Many types of air handling system are used in buildings. Before attempting this type of measurement in any building the suitability of the installed system must be assessed. This technique requires the system to be operated in a non-standard manner. Basically it must be possible to arrange the ventilation system so that the building becomes either pressurized or depressurized. In pressurization, for example, it must be possible to operate the supply fans while the return and exhaust fans are turned off. Return dampers must also be closed so that supply air flowing into the building can only leave the interior through outside doors, windows and other leakage sites. The system air flow rate must be controllable through an appropriate range by adjusting damper positions, fan speeds and/or the number of fans in operation.

It is recommended that the building services site engineer be consulted at all stages of the setting up procedure, thus making full use of detailed information about the operation of the air handling system.

Flow Rate Measurement

Several methods are available for the measurement of air flow rates in ventilation systems. An examination of all these techniques is beyond the scope of this report and they are well documented elsewhere (See for example Svensson [1983]). One particular technique will, however, be examined in detail. This method has been chosen for two reasons. Firstly because it has been applied successfully to internal fan pressurization measurements in a variety of buildings systems (Persily [1986]), and secondly because it has been developed from the same principles as the constant emission rate method for evaluating building air change rates (see Section 2.1.2).

Some air flow measurement methods require long straight sections of duct preceding and/or following the measurement plane. With these methods if there is insufficient distance between the measurement point and the nearest disturbance to the flow (e.g. bend, damper or fan), then large errors in the measurement result may occur.

If, however, a tracer gas is used for the measurement of air flow rate then the distance from the nearest disturbance to the flow becomes less critical. Indeed it can be an advantage to have induced turbulence at the measurement location. This is because the tracer gas method described here is most effective when a homogeneous mixture of air and tracer can be maintained.

The method is based on injecting a known flow rate of tracer gas into the ventilation duct, usually at the upstream side of the supply fan. Further downstream when the tracer gas has become well mixed with the air by the fan, the tracer concentration is continuously monitored. Under conditions of good mixing the air flow rate can be determined from the tracer injection rate and the measured concentration using

$$Q = \frac{I}{C} \qquad [6.8.1]$$

Where

Q = Air flow rate through ventilation system m^3s^{-1}

I = Injection rate of tracer into ventilation system

C = Concentration of tracer in ventilation system

If the air in the duct contains a certain initial concentration of tracer gas (this may occur due to recirculation via leaky return dampers, but should be avoided if possible) then a correction factor must be applied to the above equation, which becomes

$$Q = \frac{I}{(C - C_d)} \qquad [6.8.2]$$

Where

C_d = Initial concentration of tracer gas in duct

The gas flow rate can be measured with a calibrated float type variable orifice meter and the tracer concentration is evaluated using a suitable analyser. In this way the flow rate through the ventilation system is calculated.

<u>Pressure Differential</u>

Many types of instrument are available for the measurement of the pressure differential which is created across the building envelope (see, for example Section 7.3). Internal and external pressure taps must be made and the instrument must be able to evaluate pressure differences approximately in the range (0-60 Pa).

6.8.4 SETTING UP AND OPERATING DETAILS

The first task is to ensure that the air-handling system on site can be configured to enable an overpressure or underpressure to be created within the building. Ideally no air should return to the ventilation supply fan. A schematic of an ideal internal fan configuration for this method has already been shown in Figure 3.1.2. Once the system has been set up the flow measurement device, tracer gas or otherwise, is installed. Pressure differential measurement devices are then located. With large buildings such as those often examined by this method it is often preferable to measure the differential pressure at more than one location on the building envelope. This is because the larger the building the more the natural pressure differences caused by wind and temperature will vary over the envelope and it may be necessary to obtain an average value for this parameter.

The measurement at more than one location can be performed by having several instruments or by having a single measurement device linked to a variety of pressure taps via lengths of tubing and a pressure selection switch. The exact number and location of the pressure taps depends upon the building shape and size. They should cover a range in height and be placed on more than one side of the building.

By adjusting the outside air intake dampers, the intake dampers on the fan or the fan speed itself, the air flow rate can be set to the required level. Once steady-state conditions have been reached then measurements of the flow rate and pressure differentials can be made. Subsequent measurements are made after alterations to the flow rate.

A range of pressure differentials should be examined and the actual range available will depend upon the volume and leakiness of the building as well as the air moving capabilities of the fan. The final data obtained from the test consists of pairs of values of the air flow rate and average pressure differential across the envelope.

6.8.5 PRESENTATION OF RESULTS

The presentation of the results of this type of measurement is very similar to that of pressurization tests performed using external fans. This is examined in Section 3.3 and will not be discussed further here. However, when using this measurement technique it may not be possible to achieve a pressure difference of 50 Pa across the envelope. Therefore if the air change rate of different buildings at the same pressure difference is to be compared, then a lower pressure differential may have to be used.

6.8.6 MEASUREMENT ACCURACY

Two main parameters are measured in this method, the flow rate through the ventilation system and the pressure differential across the envelope. The flow rate through the system is usually evaluated by an indirect method such as the tracer gas technique described in Section 6.8.3. If this method is used then tracer gas injection rates and tracer concentration must be evaluated. Using a calibrated flow meter it is possible to evaluate the tracer gas flow rate to an accuracy of ± 1% and a good quality analyser can be used to estimate the tracer concentration to ± 2%.

Pressure differential measurements can be made with a variety of instruments and it should be possible to evaluate pressure differentials at individual points across the building envelope to ± 2%. With large buildings there may be a range of pressure differentials existing across various points on the envelope and care must be taken when assigning a single value to this parameter. The variation of pressure differential can be minimised by making measurements under calm conditions and low temperature differentials. While no standard exists for the internal fan pressurization technique it is recommended that measurements be made when the wind speed is less than 2 m/s and the indoor outdoor temperature difference is not greater than 20 °C.

6.8.7 COMMENTS

Because of the disruption this technique causes to this normal operation of the air-handling system, this type of measurement must be used with care and preferably when any disturbance to the building occupants will be at a minimum.

6.8.8 AVAILABILITY OF MEASUREMENT SYSTEM

The ability to perform this type of measurement relies entirely on the availability and suitability of the air-handling system in the building to be tested.

For further information on the use of this technique contact:

Andy Persily
Building Thermal and Service Systems Division
Centre for Building Technology
National Bureau of Standards
Washington D.C. 20234
USA

Tel: 301-975-6431

REFERENCES

Specific To Technique

Persily, A.K. and Grot, R.A. [1986].
Pressurization testing of Federal buildings.
Measured Air Leakage of Buildings.
ASTM STP 904, pp184-200, 1986.

6.9.1 TYPE OF TECHNIQUE

AC PRESSURIZATION

Parameter(s) Measured

This technique evaluates the effective leakage area of a building envelope at pressure differentials similar to those created by natural wind and temperature effects.

Measurement Principle

This technique uses a piston to create a continuous sinusoidal change of a building's internal volume. In turn this creates a fluctuating pressure difference across the building envelope. This can be distinguished from naturally occurring pressure fluctuations.

By measuring the amplitude of the pressure response inside the building, and the phase relationship between the pressure and the velocity of the piston the air flow through the envelope can be evaluated. Given this computed air flow and the measured pressure differentials the effective leakage area is determined directly.

6.9.2 RANGE OF APPLICATION

This technique has been used successfully in several domestic buildings with volumes in the range 300-530 m^3. Its only real limitation lies in its inability to measure large leaks such as undampered chimneys or open windows. Tests have shown that leaks over some critical size are treated by AC Pressurization as though they were equal to that critical size.

6.9.3 EQUIPMENT AND INSTRUMENTATION

General Description

Any AC Pressurization test apparatus must include components which perform the following basic functions.

Volume Drive

The purpose of the drive component is to provide a sinusoidal change in the internal volume of the building, at a known or specified amplitude and frequency. A frequency range of 0.2-4.0 Hz and a displacement range of 10-100 litres is adequate for residential buildings.

Displacement Monitoring

The displacement monitoring component should be able to provide an instantaneous value of the piston velocity. This is one of the two inputs used to compute the airtightness of the building. The type of displacement monitoring required will depend both on the drive component and the means by which it is driven.

Pressure Measurement

This component measures the instantaneous pressure response of the building to the induced volume changes. It is required only to measure the pressure signals at the drive frequency and its harmonics, other frequencies can be filtered out or eliminated with no loss of accuracy.

Analysis/Control

This component uses the velocity and pressure response signals to calculate and display the effective leakage area of the envelope. If automatic operation is desired then this component should be able to control the volume drive in order to attain a specified pressure response.

Specific Description of a Working Device

Several options are available for the accomplishment of each of the above named tasks. Several combinations of these options have been used to build working AC Pressurization devices. Only one such device will be described in detail here (see Figure 6.9.1). This particular device is given attention because its viability has been proven in field trials, it is commercially available and it is similar to DC Pressurization blower door equipment.

In this device the volume drive is provided by external bellows drive mounted in a door panel. A piston is connected to the flexible but airtight bellow and a scotch-yolk mechanism is used to turn the circular motion of a variable speed motor into true sinusoidal motion at the piston face. Mounting the device in a door panel facilitates portability and ease of location in the building envelope (See Figure 6.9.2).

The stroke of the scotch-yolk mechanism can be varied between 4 and 18 cm and this allows the volume drive to be adjusted between 10-50 litres. This displacement range has been found to be adequate for the testing of most domestic buildings.

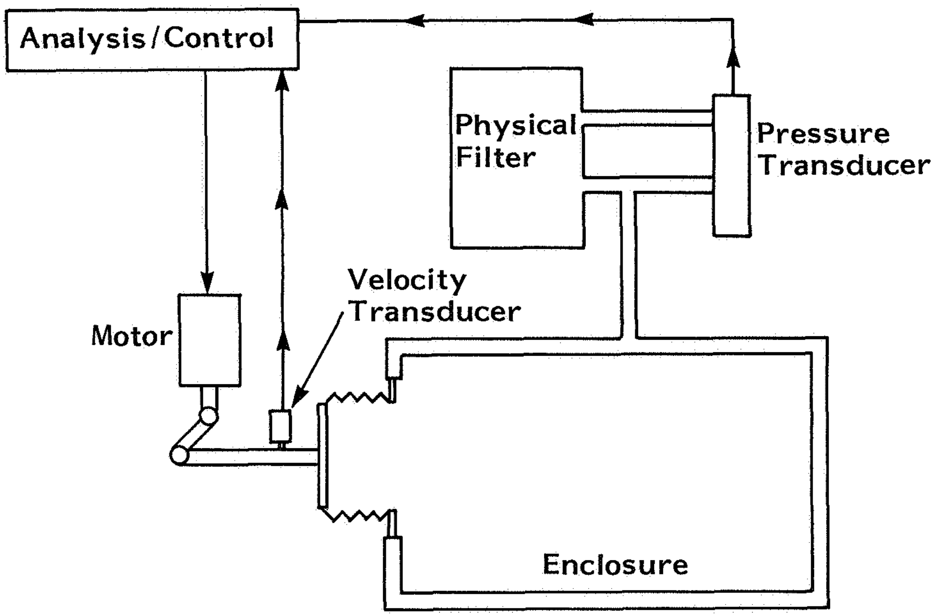
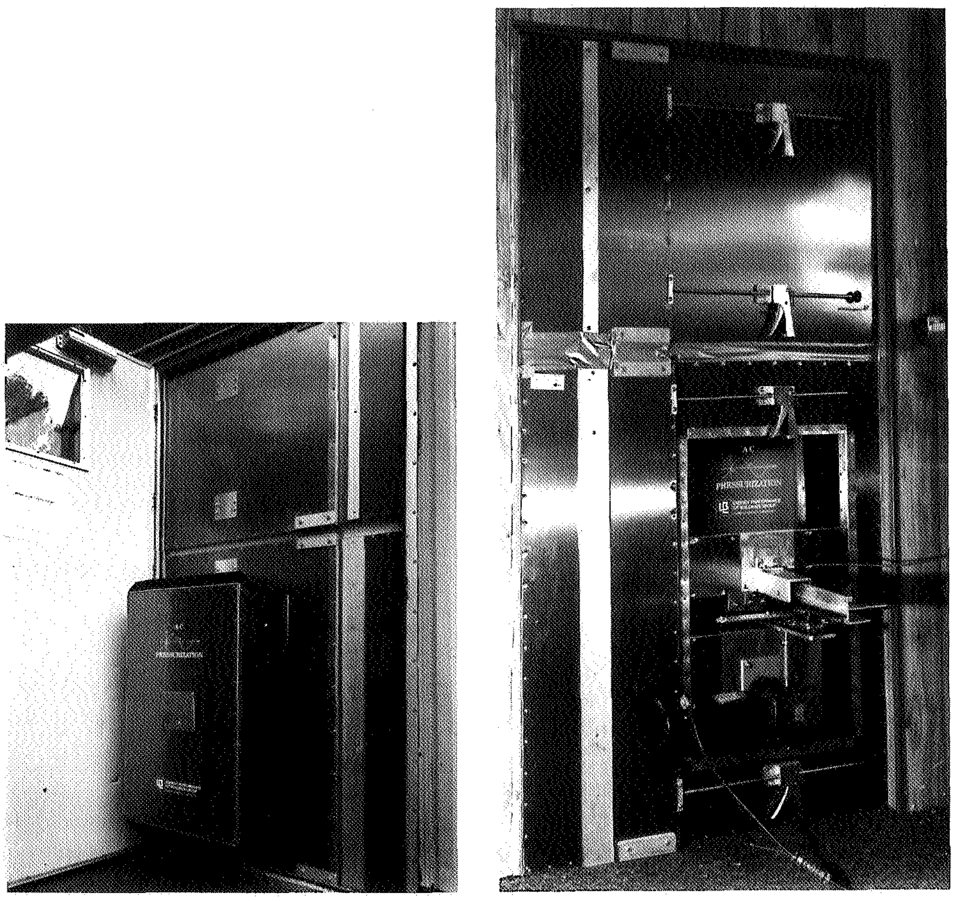


Figure 6.9.1 Schematic of AC pressurization equipment

By adjusting the speed of the DC motor the frequency of the device can be varied between 0.1 and 4 Hz. The speed of the piston is monitored by a wire-cable velocity transducer and the pressure response of the building is measured with a low frequency, AC-coupled condenser microphone which is sensitive to 0.01 Pa. Less expensive pressure transducers can be used instead of the low frequency microphone without loss of accuracy.

6.9.4 SETTING UP AND OPERATING DETAILS

For the particular device described in Section 6.9.3 the main setting up procedure consists of fitting the door panel into a suitable exterior door frame and placing the pressure measurement microphone inside the building. This procedure requires approximately the same time as required for installing a DC Pressurization apparatus. The actual measurement time is short, approximately 3 minutes for a leakage area measurement. Tests have shown that the position of the microphone does not affect the measured pressure signal even when placed on the second floor of a two storey house. When preparing the building for the test it must be noted that there is a limitation to the size of leaks which will be detected by AC Pressurization. So wide open windows and undampered chimneys may not be correctly evaluated.



Internal External

Figure 6.9.2 Internal and external views of AC pressurization equipment

6.9.5 PRESENTATION OF RESULTS

This technique evaluates the equivalent leakage area of the building envelope at a chosen reference pressure. The equivalent leakage area is determined by assuming that the flow through the envelope is similar to perfect orifice flow (see Section 3.3). The reference pressure is often taken as 4 Pa. This pressure differential is often representative of pressure differences created by natural forces. Ideally when examining several buildings the results should be presented in a tabular format which includes other information about the building structure.

6.9.6 MEASUREMENT ACCURACY

The results obtained by this relatively new technique have been compared with those obtained from the more well known DC Pressurization method (blower door tests). This type of comparison has shown that the values for leakage area obtained by DC and AC Pressurization agree reasonably well, but that the AC values are consistently lower than corresponding DC results. Because neither technique is a primary standard it cannot be determined which one is correct.

For example there may be systematic errors associated with DC Pressurization due to the fact that leakage values quoted at low pressure differentials (e.g. 4 Pa) have been extrapolated from measurements made at much higher pressures.

However, AC Pressurization might yield lower values than DC Pressurization due to the effect of large leaks. In one test using the AC door panel the leakage through a window was measured as it was opened further and further. The result of this was that the measured leakage area increased with window opening up to a certain point after which the opening no longer affected the measured leakage area. This indicates that leaks over some critical size are treated by AC Pressurization as though they were equal to that critical size. For the normal operating frequencies of AC Pressurization the critical size of window opening is between 10-20 cms.

For some applications the measurement of large leaks is not required so this critical leakage area factor must be seen only as a limitation and not an absolute disadvantage.

6.9.7 COMMENTS

AC Pressurization has several important advantages over its DC counterpart. It operates at pressures which normally drive infiltration. The measurement and analysis is done in real time, so the leakage area is measured continuously and essentially instantaneously, and only small volumes of air are exchanged with the atmosphere. The AC Pressurization technique is also less sensitive to wind pressures than DC Pressurization. This shows measurements to be made under variable wind conditions without degrading accuracy. Finally with a different choice of options for performing the tasks presented in Section 6.9.3 a device could be built which would perform AC Pressurization without piercing the building envelope.

6.9.8 AVAILABILITY OF MEASUREMENT SYSTEM

The AC Pressurization system in its door panel form is commercially available. For further information contact:

David Saum
Infiltec
5597 Seminary Road, Suite 2412 South.
PO Box 1533
Falls Church
Virginia 22041
USA.

Tel: 0101 703 - 820 - 7696

For specific technical and research information contact:

Mark Modera
Lawrence Berkeley Laboratory
University of California
Berkeley
CA 94720 USA

Tel: 0101 415 - 486 - 4022

REFERENCES

Specific To Technique

Modera, M.P. and Sherman, M.H. [1985].
AC Pressurization:
A Technique for Measuring the Leakage Area in Residential Buildings.
ASHRAE Symposium on Air Leakage Analysis Techniques.
June 23-26, 1985, Honolulu, Hawaii
ASHRAE Transactions, Vol 91, Part 2.

CHAPTER 7: Detailed Description of Instrumentation

CHAPTER 7 DETAILED DESCRIPTION OF INSTRUMENTATION

The measurement of air exchange rates and airtightness often requires the use of specialist equipment and instrumentation. Equipment used for air exchange rate and airtightness measurements has been previously discussed in general terms in Chapter 4. An objective of this Chapter is to provide more detailed information about several instruments which can be used for air infiltration or ventilation measurements.

Information about each instrument is presented in a standard format, thus enabling specific details to be easily located. The instrument description is presented under the following headings:

1 Manufacturer

2 Measured Parameter

3 Range

4 Precision

5 Response Time

6 Method of Measurement

7 Input Requirements

8 Display

9 Other Output

10 Power Requirements

11 Range of Ambient Conditions

12 Weight and Dimensions

13 Accessories

14 Possible Applications

CAUTION

The Air Infiltration and Ventilation Centre does not necessarily endorse any instrument described in this chapter. Where a specific manufacturer is presented this does not necessarily indicate that other manufacturers or suppliers of the instrument or similar instrument do not exist. Similar instruments may be equally suited to the applications described here. Manufacturers and suppliers of instruments often vary from country to country. Further information about instruments used in air exchange rate and airtightness measurements can be obtained from the Air Infiltration and Ventilation Centre or its representatives. A list of suggested contacts is presented in Table 7.1.

No responsibility can be accepted for the accuracy of information presented in this chapter, nor for the suitability of specific instruments for air exchange rate or airtightness applications. Exact specifications of any instrument should always be obtained directly from the manufacturer when considering purchase. Current price details should also be obtained from the manufacturer.

TABLE 7.1. SUGGESTED CONTACTS FOR COUNTRY SPECIFIC INSTRUMENTATION DETAILS

Belgium
P. Wouters,
Belgian Building Research Institute,
Lombard Street 41,
1000 Brussels,
Belgium.
Tel: 02-653-8801/02-511-0683
Telex: 25682

Canada
M. Riley, Chief,
Residential Technology and
Industrial Development,
New Housing Division,
Energy Conservation Branch,
Energy, Mines and Resources Canada,
Ottawa, Ontario, K1A 0E4
Canada.
Tel: 613-995-2133
Telex: 0533117

Denmark
P.F. Collet,
Technological Institute,
Byggeteknik,
Post Box 141, Gregersensvej,
DK 2630 Tastrup, Denmark.
Tel: 02-996611
Telex: 33416

Finland
R. Kohonen,
Technical Research Centre,
Laboratory of Heating and Ventilation,
Lampomiekenkuja 3,
SF-02150 Espoo 15,
Finland.
Tel: 358 04564742
Telex: 122972

Federal Republic of Germany
L.E.H. Trepte,
Dornier System GmbH,
Postfach 1360,
D-7990 Friedrichshafen 1,
Federal Republic of Germany.
Tel: 07545 82244
Telex: 734209-0

Italy
M. Masoero,
Dipartimento di Energetica,
Politecnico di Torino,
c.so Duca delgi Abruzzi 24,
10129 Torino,
Italy.
Tel: (39) 011 55661
Telex: 220646 POLITO

New Zealand
M. Bassett,
Building Research Association of New Zealand Inc
(BRANZ),
Private Bag,
Porirua,
New Zealand.
Tel: Wellington 04-357600
Telex: 30256
Fax: 356070

Netherlands
W. de Gids,
TNO Division of Technology for Society,
P.O. Box 217,
2600 AE Delft,
Netherlands.
Tel: 015-696900
Telex: 38071

Norway
J.T. Brunsell,
Norwegian Building Research Institute,
Box 322,
Blindern,
N-0314 Oslo 3,
Norway.
Tel: 02-46-98-80

Switzerland
P. Hartmann, EMPA,
Section 176,
Ueberlandstrasse
CH 8600 Duebendorf,
Switzerland.
Tel: 01-823-4276
Telex: 825345

Sweden
J. Kronvall,
Lund University,
P.O. Box 118,
S-22100 Lund
Sweden
Tel: 46.107000
Tlx: 33533

USA
M. Sherman,
Energy and Environment Division,
Building 90, Room 3074,
Lawrence Berkeley Laboratory,
Berkeley, California 94720.
USA.
Tel: 415/486-4022
Telex: 910-366-2037
Fax: 415.486.5172

United Kingdom
Air Infiltration and Ventilation Centre
Barclays Venture Centre
University of Warwick
Science Park
Sir William Lyons Road
Coventry CV4 7EZ

7.1 Instrument

ELECTRON CAPTURE DETECTOR WITH
GAS CHROMATOGRAPH - TYPE AI 505

7.1.1 Manufacturer

A I Industrial
London Road
Pampisford
Cambridge
CB2 4EF
United Kingdom Tel: Int +44 223 834420

7.1.2 Measured Parameter

Concentration of sulphur hexafluoride.

7.1.3 Range

Sulphur hexafluoride lower detection limit, 1 part sulphur hexafluoride in 10^{11} parts of air. Will detect concentrations up to 1000 ppm.

7.1.4 Precision

Quick calibration checks are required to a known tracer gas concentration. The instruments response is linear over range.

7.1.5 Response Time

Instrument takes several minutes to reach stable conditions after switching on. A sample of air containing sulphur hexafluoride can be processed and analysed in approximately 30 seconds.

7.1.6 Method of Measurement

The instrument contains four essential components; a pump, a sample valve, a chromatograph column and an electron capture detector. The pump continuously draws argon through the column and passes it through pipework to the vent port of the instrument.

When the sample valve is operated a small volume (0.5 cc) of air is isolated and carried to the gas chromatograph column by argon carrier gas. The carrier gas is supplied from a small cylinder attached to the back of the instrument.

In sample mode the gas chromatograph column separates the sulphur hexafluoride from the atmospheric oxygen before the gas sample reaches the detector. In the column the gas is absorbed and desorbed at a different rate to air by the column packing, causing the tracer gas to arrive at the detector end of the column after atmospheric oxygen, and this is detected separately.

The electron capture detector comprises of two oppositely charged electric plates and a radioactive particle source (10 mc). The source causes an excess of negative ions in the detector. These are collected at the positively charged plate causing a current flow (standing current). When an electron absorbing gas passes through the detector cell it captures a quantity of electrons. The standing current drops. This drop in standing current can be measured and related to the concentration of the gas.

The signal from the detector is fed into an amplifier and the read-out is presented by an analogue meter mounted on the front of the instrument.

7.1.7 Input Requirements

The instrument should be connected to a probe which leads to the measurement location. Probes are supplied with the instrument.

7.1.8 Display

Analogue display.

7.1.9 Other Output

0-80 millivolts

Voltage output is via standard electrical jack-plug and socket with a coaxial lead. This is ideal for connecting the detector to a chart recorder or data logger.

7.1.10 Power Requirements

The instrument can operate continuously from an AC supply using the supplied battery charger. Alternatively the batteries in the charger can be used for a period of up to 10 hours before recharging is required (Recharging time 14 hours).

7.1.11 Range of Ambient Conditions

Instrument will operate under the range of conditions normally found in buildings. The detector can experience slight thermal drift and may have to be re-zeroed during long periods of use.

7.1.12 Weight and Dimensions

3-4 kg (approx)
350 x 250 x 350 mm (approx)

7.1.13 Accessories

The detector is supplied with the battery charger/adaptor and a small argon gas cylinder. A gas filling jig can be supplied which enables the small cylinder to be refitted from a large high pressure argon cylinder.

7.1.14 Possible Applications

This instrument has found several applications in air exchange rate measurements. Three are outlined below.

Simple site measurement of the decay rate of sulphur hexafluoride tracer gas. A leaflet describing this technique can be obtained from the instrument manufacturers. Further details of this technique can be found in Section 6.1.

Laboratory based analysis of air/tracer obtained by bottle sampling in measurement buildings. Further details of this technique can be found in Section 6.2.

Adaption of basic instrument for more sophisticated interzonal air flow measurements using multiple tracer methods. Further details of this technique can be found in Section 6.6.

7.2 Instrument

INFRA-RED GAS ANALYSER - TYPE MIRAN 1A

7.2.1 Manufacturer

The Foxboro Company
151 Woodward Avenue
PO Box 5449
South Norwalk
Connecticut
06856 5449
U.S.A. Tel: Int +203 8531616

7.2.2 Measured Parameter

Evaluation of the concentration of a wide variety of infra-red absorbing gases (see Table 4.1.1).

7.2.3 Range

Depends upon gas being analysed. Two commonly used tracer gases are:

Nitrous oxide
minimum detectable concentration = 0.2 ppm

Sulphur hexafluoride
minimum detectable concentration = 0.01ppm

The instrument can evaluate air sample containing several percent by volume of tracer gas.

7.2.4 Precision

Generally accepted ± 2%.

The manufacturer can supply a closed loop calibration system. This essentially consists of a syringe which is used to inject known volume of gas into the sample cell of the instrument. The sample cell has a known volume (5.6 litres), hence the instrument can be calibrated for gas concentration.

7.2.5 Response Time

The instrument operates continuously. For a step change in concentration the instrument takes in the order of 40 seconds to indicate the true concentration in the cell. However, if a step change does occur, the indicated concentration reaches 95% of the true concentration in 15 seconds.

7.2.6 Method of Measurement

Many gases can be analysed by infra-red. Infra-red energy striking a chemical compound can cause vibrations or rotations of the molecules to occur. This results in energy absorption. These vibration frequencies depend on the molecular structure of the compound and correspond to specific wavelengths in the infra-red. The instrument measures the amount of infra-red absorbed at these selected analytical wavelengths and the amount of absorption measured is converted into gas concentration.

The Miran-1A consists of two assemblies: the infra-red spectrometer and the gas sampling cell. A variable infra-red filter is utilized, this can be set at any wavelength within its range thus allowing a variety of gases to be analysed.

The number of times the infra-red beam passes through the sample can also be controlled. This gives the instrument the ability to measure a wide range of concentrations of gases. Air is drawn through the cell by using a small integral pump (flow rate 30 l/min) on the exhaust side of the sample cell.

7.2.7 Input Requirements

The instrument should be connected to a sampling hose. A 3 metre long hose is supplied with the instrument. Ambient air should be passed through a particulate filter

7.2.8 Display

An analogue meter provides a read-out in absorbance units for direct conversion to concentration.

7.2.9 Other Output

0-1 Volt
Standard output jack for chart recorder or datalogger.

7.2.10 Power Requirement

25 Watt
115 or 230 volt (built in switch) 50 or 60 Hz.

7.2.11 Range of Ambient Conditions

Will operate under the range of conditions normally found in buildings.

7.2.12 Weight and Dimensions

Weight: 14 kg
Dimensions: 190 x 280 x 720 mm with air sample cell.

7.2.13 Accessories

The main accessory for this instrument is the closed loop calibration system. This includes septum, pump, teflon connecting tubes and stainless steel fittings for connection to the analyser.

7.2.14 Possible Applications

This instrument has found several applications in air exchange rate measurements. One specific example is its use in the constant concentration tracer gas technique described in Section 6.5.

7.3 Instrument

ELECTRONIC MICROMANOMETER - TYPE MP6 KSR

7.3.1 Manufacturer

Air-Neotronics Limited
Monument Industrial Park
Chalgrove
Oxford
OX9 7RW
United Kingdom — Tel: Int +44 865 891190

7.3.2 Measured Parameter

Positive, negative or differential pressures.
Direct velocity read-out from pitot tubes.

7.3.3 Range

Single instrument has eight pressure ranges including:

0 to 199.9 Pa
0 to 1999 Pa
0 to 6 kPa

and velocity range:

0 to 100.0 m/s

7.3.4 Precision

(a) Accuracy (manufacturer's statement):
Better than 1.0% of reading throughout all velocity and pressure ranges.

(b) Zero drift:
Less than 1 Pa per °C.
The instrument has an automatic re-zeroing function.

(c) Linearity:
The linearity of each range is better than ± 0.5%.

7.3.5 Response Time

Instrument responds fully to pressure changes in less than 1 second.

7.3.6 Method of Measurement

The instrument is based on a differential capacitance transducer. Essentially, this consists of a taut metal diaphragm suspended between two closely spaced metal electrodes. The electrodes are electrically insulated from the diaphragm, each electrode forming with the diaphragm a small air-gap capacitor. The diaphragm divides a pneumatic chamber, the two halves of which are connected to the instrument's pressure ports. The whole arrangement is precisely symmetrical.

When a pressure is applied across the diaphragm, it deflects towards one of the electrodes and away from the other. This causes the capacitance of the electrode gaps to become unequal. The diaphragm movement is sensed electronically by supplying each electrode with a precisely similar AC signal, and measuring the difference in signal attenuation on each side of the transducer due to the capacitance changes. The attenuation is proportional to the capacitance, and the difference between the two signals is thus proportional to the applied pressure.

The transducer is arranged in an AC full bridge circuit. The bridge excitation signal is derived from a quartz crystal oscillator, binary divided to provide the desired frequency. Amplitude stabilisation is provided by a band-gap reference diode in a high gain closed loop circuit, and the signal is passed through a low-pass filter before being applied to the bridge. These measures provide an excitation signal which is precisely controlled in frequency, amplitude and waveform.

The bridge output is a differential AC signal, the components of which are DC referenced and peak-level-detected in a single monolithic integrated circuit before being smoothed and buffered. The final stage of the circuitry is a switched-gain differencing amplifier which drives the instrument display and provides an analogue output signal.

7.3.7 Input Requirements

Two 2mm bore pressure ports.

7.3.8 Display

Digital display with smallest division 1 Pa.

7.3.9 Other Output

0-1 Volt (for each range).
Voltage output via miniature electrical jack-plug and socket.

7.3.10 Power Requirements

4 X MN1604 pen batteries (1.5V).
Current consumption: 10 mA
Battery life: up to 70 hours depending upon usage

7.3.11 Range of Ambient Conditions

0 to 50 °C for working.
-5 to 55 °C for storage.

7.3.12 Weight and Dimensions

Weight: 925g (with battery)
Dimensions: 199 x 98 x 62 mm

7.3.13 Accessories

Instrument is supplied with:

1 x carrying case
2 x 3m long silicone rubber tube
1 x pitot tube adapter block for use with certain styles of pitot tubes
1 x miniature jack-plug for electrical output socket
1 x operating and calibration instruction booklet

The manufacturer also produces an extendable pitot tube designed for use in conjunction with instrument.

7.3.14 Possible Applications

Pressure:
Pressure differential across building envelope during DC pressurization tests - See Section 3.1.1.
Pressure differential across blower door fan in order to evaluate air flow through fan - See Section 4.3.

Velocity:
Air flow velocity measurements in ventilation system ducts. Pitot tube required from manufacturer.

APPENDIX 1

GLOSSARY

AC pressurization technique

Evaluating the air leakage of a building using a piston assembly to vary the effective volume of the structure and measuring the pressure response due to this variation.

acoustic technique

A method of detecting cracks in a building where leakage may occur by placing a steady source of high pitched sound within the building and using a microphone outside as a detector. Leaks correspond to an increase in volume of the sound transmitted. This technique provides qualitative information only.

adventitious opening

An opening in the building envelope which in terms of ventilation is unintentional. e.g., cracks around windows and doors.

air change rate

The ratio of the volumetric rate at which air enters (or leaves) an enclosed space divided by the volume of that space. Often this is expressed in air changes per hour.

air exchange rate

General term relating to the rate of air flow between one space and another. This can be between various internal zones of a building or between the building and the atmosphere.

air exfiltration

The uncontrolled leakage of air out of a building.

air flow rate

The mass/volume of air moved in unit of time. (The transport may be within an enclosure or through an enclosing envelope).

air infiltration

The uncontrolled inward air leakage through cracks and interstices in any building element and around windows and doors of a building (i.e., adventitious openings), caused by pressure effects of the wind and/or the effect of differences in the indoor and outdoor air density.

air infiltration characteristic

The relationship between the flow rate of air infiltration into a building and the parameters which cause the movement.

air leakage

The flow of air through a component of the building envelope, or the building envelope itself, when a pressure difference is applied across the component.

air leakage characteristic

An expression which describes the air leakage rate of a building or component. This may be:

(a) the air leakage flow rate at a reference pressure difference across the component or building envelope.

(b) the relationship between flow rate and the pressure difference across the building envelope or component.

(c) the equivalent leakage area at a reference pressure difference across the component or building envelope.

airtightness

A general descriptive term for the leakage characteristics of a building.

background leakage

Leakage of air through a building envelope which is not accounted for by obvious measurable gaps.

balanced fan pressurization

Technique utilizing two or more blower doors to evaluate the leakage of individual internal partitions and external walls of multizone buildings. Technique involves using the fans to induce a zero pressure difference across certain building components, thus eliminating their leakage from the measurement.

balanced ventilation

A system in which fans both supply and extract air from the enclosed space, the supply and extract flow rates being equal. Such a system allows air to air heat recovery.

blower door

A device that fits into a doorway for supplying or extracting a measured flow rate of air to or from a building. It is normally used for testing for air leakage by pressurization or depressurization.

boundary layer (atmospheric)

The atmospheric boundary layer is that region of the atmospheric surface layer which is directly affected by the friction between the ground and the atmosphere.

building component

General term for any individual part of the building envelope, usually applied to doors, windows and walls.

building envelope

The total of the boundary surfaces of a building, through which heat (or air) is transferred between the internal spaces and the outside environment.

capacitance pressure transducer

A device with a metal diaphragm sensing element acting as one plate of a capacitor. When pressure is applied it moves with respect to a fixed plate, changing the thickness of the dielectric between. The resulting signal is monitored using a bridge circuit.

collector chamber

Sealed box or other enclosure used to isolate a building component when conducting pressurisation tests.

component leakage

The leakage of air through the building envelope or internal partitions, which is directly attributable to flow through cracks around doors, windows and other components.

connected space

A space in a building adjacent to the measurement space with which significant exchange of air may take place, thus increasing the effective volume of the space.

constant concentration technique

A method of measuring ventilation rate whereby an automated system injects tracer gas at the rate required to maintain the concentration of tracer gas at a fixed, predetermined level. The ventilation rate is proportional to the rate at which the tracer gas must be injected.

constant emission rate technique

A method of measuring ventilation rate whereby tracer is emitted continuously at a uniform rate. The equilibrium concentration of tracer gas in air is measured.

contaminant

An unwanted airborne constituent that may reduce the acceptability of the air.

continuity equation

Mathematical expression relating to the conservation of matter, an example of which is the equation equating the flow of tracer gas into a space with the flow of tracer gas out of a space This particular equation is the basis for evaluating air exchange rates from tracer gas measurement.

cup anemometer

A device for measuring wind speed comprising a number of cups attached around a spindle to which an indicator is fitted. Widely used in meteorological studies.

decay rate technique

A method of measuring ventilation rate whereby a quantity of tracer gas is released and the decrease in concentration measured as a function of time.

depressurization

Term used to describe fan pressurization when a static under pressure is created within the building.

discharge coefficient

A dimensionless coefficient relating the mean flow rate through an opening to an area and the corresponding pressure difference across the opening.

displacement flow

With this type of flow incoming outdoor air displaces internal air without mixing.

effective volume

The volume of the interior building (or room) in which mixing occurs.

electron capture analyser

An instrument which uses a weak beta source to generate electrons in an ionisation chamber, which is subjected to a pulsed voltage, thus generating a current. Electron capturing material in the sample reduces the number of electrons in the chamber and thus the current. This reduction can be calibrated in terms of tracer gas concentration, hence the concentration of tracer gas in an air sample can be evaluated.

equivalent leakage area (ELA)

The equivalent amount of orifice area that would pass the same quantity of air as would pass collectively through the building envelope at a specified reference pressure difference.

extract ventilation

A mechanical ventilation system in which air is extracted from a space or spaces, so creating an internal negative pressure. Supply air is drawn through adventitious or intentional openings. Such a system allows heat to be recovered from the extracted air.

fan pressurization

General term applied to any technique involving the production of a steady static pressure differential across a building envelope or component. Often referred to as DC Pressurization.

flow coefficient (k)

In the power function approach this parameter is used in conjunction with the "flow exponent" to quantify flow through an opening.

flow equation

Equation describing the air flow rate through a building (or component) in response to the pressure difference across the building (or component). These equations are usually power law or quadratic in form.

flow exponent (n)

In the power function approach this parameter characterises the type of flow through a component. (n=1 represents laminar flow, n=0.5 represents turbulent flow). For most flow paths, n takes a value between these extremes.

fortuitous leakage

Uncontrolled air leakage through building envelope due to the natural action of wind and temperature, i.e., air infiltration.

gas chromatography

A process by which gases can be separated from one another. Used in this application to separate tracer gases from each other and from the constituents of air, thus allowing individual analyses to be performed.

grab sampling method

Any tracer gas method where air/tracer samples are obtained from a building and analysed afterwards in a laboratory.

indoor air pollution

Pollution occurring indoors from any source i.e., from outside as well as inside the building.

infra-red gas analyser

Instrument used to determine tracer gas concentrations by determining the transmission of infra-red radiation at an absorption frequency through a fixed path length.

interzonal air flow

General term applied to the process of air exchange between internal zones of a building.

leakage path

A route by which air enters or leaves the building or flows through a component.

leakage site

A point on the outer or inner surfaces of a building envelope or an internal wall where a leakage path emerges.

leeward

Downwind side of any object.

manometer

A device for measuring pressure employing the principle of displacement of liquid levels in a liquid filled "U" tube. The limbs of the "U" may be vertical, inclined or curved.

mechanical ventilation

Ventilation by means of one or more fans.

minimum ventilation requirements

The minimum quantity of outdoor air entering a building required to maintain acceptable indoor air quality.

mixing

The degree of uniformity of distribution of outdoor air or foreign material in a building.

mixing fan

Small electric fan used to aid the mixing of room air and tracer gas before and/or during a measurement.

multiple tracer gas technique

General term applied to measurement methods using two or more tracer gases. These methods are often used to evaluate interzonal air flows.

multizone

A building or part of a building comprising a number of zones or cells.

natural ventilation

Ventilation using only purpose provided openings and the natural motive forces of wind and temperature difference.

normalised leakage area

Equivalent leakage area expressed per unit building envelope area.

occupant behaviour

The pattern of activity of occupants of a building, including number of occupants, where they are within the building, what length of time and how they interact with the ventilation systems.

orifice plate

A device for measuring gas flow by measuring the pressure drop across an orifice in the flow line.

outdoor air

Air from free atmosphere that is generally assumed to be sufficiently uncontaminated to be used for ventilation.

passive sampling

Method of sampling tracer gas in a building by the process of passive diffusion.

pollution migration

Descriptive term for the movement of indoor air pollutants throughout a building.

pollution source

Any object, usually within a building, which produces a substance which will contaminate the internal environment.

pressurization

Term used to describe fan pressurization when an excess static pressure (over-pressure) is created within the building.

pressure differential

Usual term for the difference in pressure across building envelope or component whether caused by natural or artificial means.

pressure tap

Point at which pressure is measured.

purpose provided openings

Openings in the building envelope for the specific purpose of supplying or extracting ventilation air.

reductive sealing method

A method of determining the leakage of specific building components by pressurizing the building and recording the leakage changes as components are sealed successively. When all the major outlets and component cracks are sealed, the remainder is the background leakage.

retrofit

The process of reducing energy loss in a building by physical means, e.g. reducing excess air infiltration by obstructing flow through cracks and openings.

sample container

Container used to obtain a sample of air/tracer mixture from a measured building. The sample is usually returned to laboratory for analysis.

short circuiting

A direct flow path between an air supply point and an air extract point, i.e., air flows along the shortest path, without mixing.

sick building syndrome

Collective term for symptoms exhibited by occupants of some buildings. These include headaches, eye/skin irritation, shortness of breath and nausea. Some of these complaints are often attributed to inadequate ventilation in the buildings.

single tracer gas technique

General term applied to any method using only one tracer gas. These methods are usually used to evaluate air change rate.

single zone

Any case where a building or part of a building is considered to be a single well mixed space.

site analysis

Applied to any tracer gas measurement technique where traces of air exchange rates are determined directly at the measurement building.

smoke visualisation

A method of detecting leaks in the building fabric by pressurizing the building and using smoke to trace the paths followed by the leaking air.

specific leakage area

Equivalent leakage area expressed per unit floor area.

stack effect

Pressure differential across a building envelope caused by differences in the density of the air due to an indoor-outdoor temperature difference.

supply ventilation

A system in which air is supplied to a space(s) so creating an internal positive pressure. Air leaves the building through adventitious or purpose provided openings. Such a system does not allow heat to be recovered from the exhausted air.

tachometer

Instrument for measuring velocity or speed of rotation. Used to evaluate the speed of fans, this in turn is used to calibrate the fan in terms of air flow. Often used in blower doors.

thermography

The process of converting the heat emitted from an object into visible pictures. Used to indicate and represent the temperature distribution over part of a building envelope.

thermometer

An instrument that measures temperature.

tracer gas

A gas used with a detection device, to determine air exchange rates.

tracer gas analyser

Any instrument used to evaluate the concentration of tracer gas in a sample of air.

tracer gas injection

Any process by which tracer gas is released into a space.

tracer gas sampling

Any process by which tracer gas or air containing tracer gas is obtained for analysis.

ventilation

The process of supplying and removing air by natural or mechanical means to and from any space.

ventilation efficiency

An expression describing the ability of a mechanical (or natural) ventilation system to remove pollution originating in a space, either of a steady state or transient nature.

ventilation energy

Energy loss from a building due to ventilation.

wind vane

Device used to evaluate and/or record the direction of the prevailing wind.

windward

Upwind side of any object.

THE AIR INFILTRATION AND VENTILATION CENTRE was inaugurated through the International Energy Agency and is funded by the following thirteen countries:

Belgium, Canada, Denmark, Federal Republic of Germany, Finland, Italy, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and United States of America.

The Air Infiltration and Ventilation Centre provides technical support to those engaged in the study and prediction of air leakage and the consequential losses of energy in buildings. The aim is to promote the understanding of the complex air infiltration processes and to advance the effective application of energy saving measures in both the design of new buildings and the improvement of existing building stock.

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ISBN 0 946075 38 7

Operating Agent for International Energy Agency, Oscar Faber Consulting Engineers, Upper Marlborough Road, St. Albans, Herts, Great Britain

Printed by Information Printing Ltd., Oxford, England